The Estimation of Standing Timber Volume of a Native pine Woodland, using Aerial Photographs.

BY

YAHIA M. A. ELDOOL

B.Sc. (Bio.) University of Khartoum

B.Sc. (For.) University of Aberdeen

A Thesis submitted for the degree of Master of Philosophy at Edinburgh University.

October, 1982.

DECLARATION

This thesis is a record of the work carried out and composed by myself. It contains no material which has been accepted for the award of any other degree or diploma in any University. Reference has been made to any material previously published or written by other persons.

Yahia M. A. Eldool.

ABSTRACT

Vertical aerial photographs were used to estimate the standing timber volume of a semi-natural pine woodland in northern Scotland.

Photostratification was done first on the basis of crown cover per cent and height. Thirty strata were identified and a map was produced. Due to limited time only five strata were selected, on the basis of timber value, for a detailed study.

A two-phase stratified random sampling design (or double sampling) was used to correlate the photo crop parameters: height, stand volume and crown cover per cent as independent variables with ground volume per hectare for five strata of the same height class. Regression analysis revealed a strong relationship between photo crown cover per cent and ground volume in these strata. The estimated total stand volume for all five strata combined was 19 per cent less than the sum of individual stratum estimates, indicating the value of stratification in forest inventory.

ACKNOWLEDGEMENTS

I am extremely indebted to my supervisor Dr. John F. Blyth for his encouragement and support throughout this work. I wish to express my sincere thanks to Dr. I. Langdale-Brown for his helpful assistance in the field of aerial photography and remote sensing.

I am grateful to the Nature Conservancy Council in Edinburgh for the provision of the aerial photographs of Rothiemarchus Forest. My thanks go to the owner of the above forest Mr. Grant for giving me access to the forest to carry out my field work.

I am grateful to Sudan Government for allowing me to carry out this study and to the British Council for their financial support.

I wish also to thank Dr. Helen Talbot for her advice on the statistical aspects of this work and all those who helped in any way.

Y.M.A. Eldool
Dept. of For. and Nat. Res.
Univ. of Edin., U.K.

1/10/1982

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CHAPTER ONE

INTRODUCTION AND OBJECTIVES

CHAPTER ONE.

INTRODUCTION AND OBJECTIVES.

1.1. INTRODUCTION.

The rational development of a forest resource, whether natural or semi-natural, is very essential to the economic growth and prosperity of a country. This can be achieved through good planning and management which can only be effective on the basis of sound technical information on the location, extent, composition, condition, volume and increment of the different components of the forest. Systematic forest surveys or forest inventories are the main tools to collect such information.

Irrespective of its objective, the management of a forest requires accurate information on the volume of the growing stock as well as its quality and growth rate.

Spurr (1952) pointed out that the volume and growth of various components of a forest are of the highest importance, as are economic considerations such as size, quality and merchantability, and thus the estimation of volume and growth per unit area is the core problem of Forest Inventory.

Volume estimation is required for a number of reasons, such as determining the value of a property for sale, taxes or to help decision-making by resource managers. Regardless of the purpose, the techniques used in volume estimation can be grouped into three categories: ground sampling, photo sampling and combinations of ground and photo sampling. In this study the last technique is used because it proved to be the fastest and most economic one.

The more extensive the forest inventory, the relatively more useful aerial photography becomes in collecting information to achieve a given accuracy, and no other method is known to be cheaper and quicker (Colwell 1976).

In the main vertical aerial photographs are used because they closely resemble a map and can be used with a minimum of correction compared to oblique ones. In addition they may readily be studied stereoscopically to produce a three-dimensional image for quantitative and qualitative assessment.

Vertical aerial photographs are invaluable for forest inventory in general and for volume estimation in particular (Spurr 1948). For forestry purposes the canopy is the main source of direct information and consequently photomensuration is mainly concerned with height and crown measurements, usually crown diameter (cd) and occasionally crown area (ca) are measured directly. Since the main field parameter for volume estimation is diameter at breast height (DBH), which is not measursble on aerial photographs, an allometric relationship between cd and DBH can be used to estimate the latter. Thus tree height and crown diameter can be used to estimate tree volume.

Vertical aerial photographs (described in section 3.1) were used in this study to estimate the standing volume of a native semi-natural woodland of Scots pine <u>Pinus silvestris</u>, at Rothiemurchus Forest in north central Scotland, section 1.2. The photographs were used to stratify the forest on the basis of canopy closure and height as well as to identify tree species.

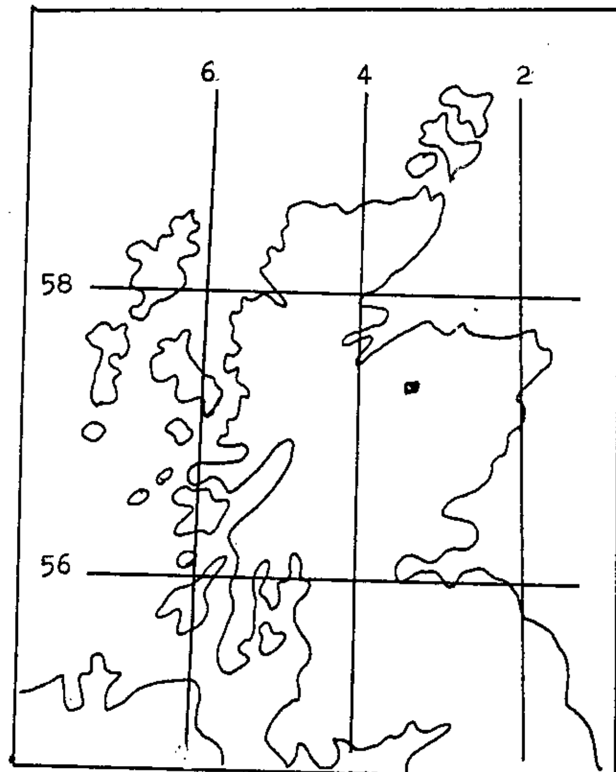
In the following chapters, a literature review in chapter 2 describes how vertical aerial photographs are used for timber volume estimation through photomensuration and photostratification. It

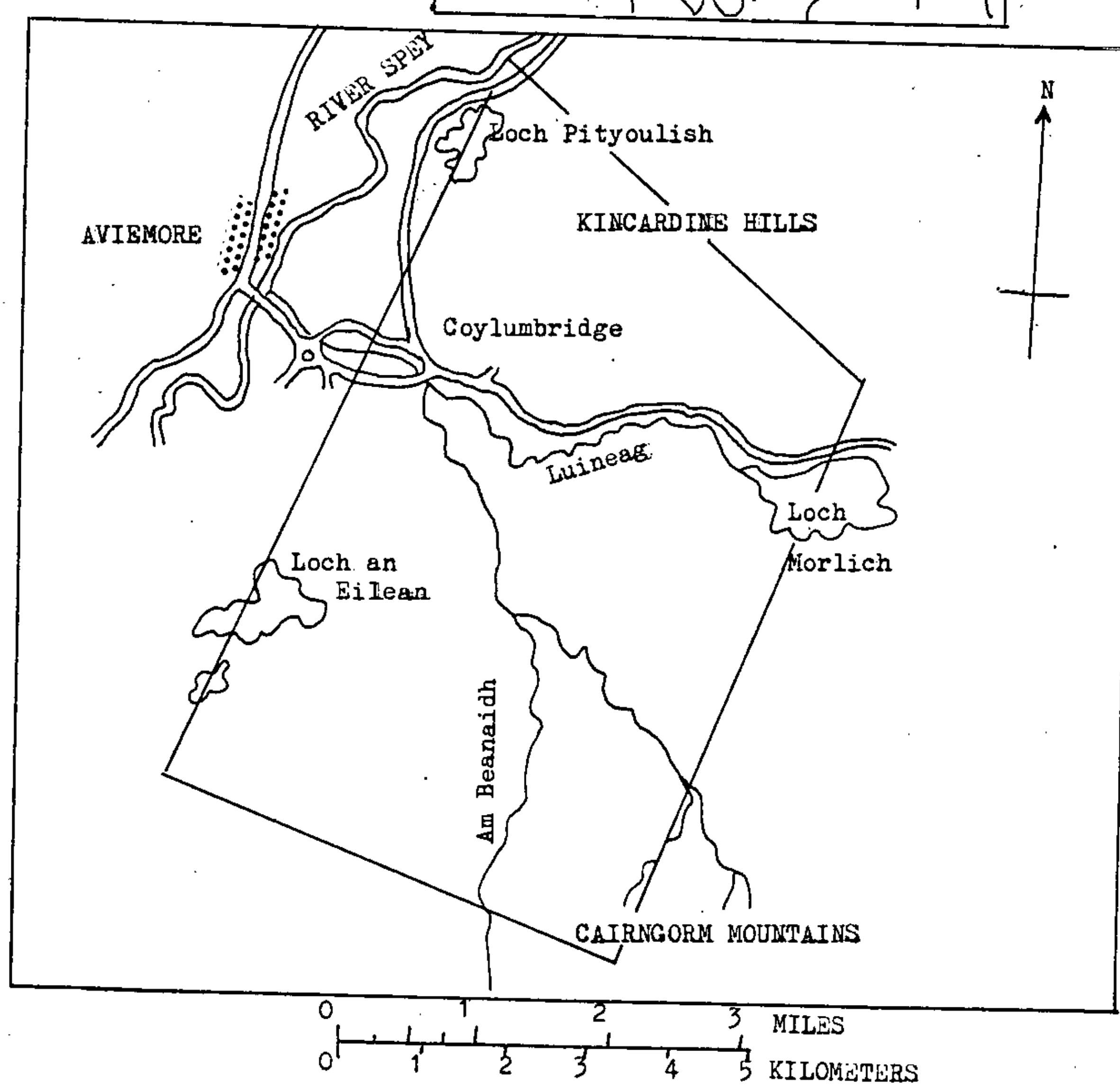
TABLE 1.1 : Annual and monthly averages of rainfall, temperature and duration of bright sunshine estimated for the period 1941 - 1970, at Glenmore Lodge Station (which is about 2 miles east of the survey area).

	Jan.	Feb.	M.	A.	May	J.	July	Aug.	Sept.	Oct.	Nov.	Dec.	YEAR.
Rainfall in mm	96	78	68	68	86	73	89	107	93	109	105	105	1077
Temperature °C													
Av. daily max.	4.1	4.4	7.1	9.9	13.3	16.3	16.8	16.5	14.6	11.4	6.9	5.0	
Av. daily min.	-2.9	-3.1	-1.2	0.8	3.3	6.4	8.0	7.7	6.4	4.1	-0.2	-1.3	
Av. daily mean	0.6	0.7	2.9	5.3	8.3	11.3	12.4	12.1	10.5	7.7	3.3	1.9	
Duration of bright Sunshine, in hours	25.2	63.6	114.0	144.3	140.2	161.8	125.2	119.2	108	90.7	37.9	15.3	1165.4

Source: Meteorological Office, Edinburgh.

FIGURE 1.1 : LOCATION OF THE SURVEY AREA.





also discusses briefly the limitations of the tool and how certain information, like form, age and increment have to be collected only from the field.

Chapter 3 describes the work methods used in tree species identification, stratification, sampling and measurements both on the photographs and in the field.

Calculations and results are presented in Chapter 4 followed by discussion of the results in Chapter 5.

1.2. THE STUDY AREA.

The survey area, Rothiemurchus Forest, covers about 4000 hectares (ha), of which 2040 ha is forest and the rest includes regeneration as well as non-forest areas like farms, moorland, bare rock and water. It lies between latitudes 57° 7′ and 57° 12′ N, and longitudes 3° 41′ and 3° 50′ W, (Figure 1.1). The area may be found in the following map: Ordnance Survey of Great Britain, 1: 1000, NH 91, Sheet number 37, 1961 edition.

The forest extends eastwards from the River Spey near Aviemore for a distance of about four miles (6.4 km).

The climate of the area is summarised as in Table 1.1.

The topography is an undulating plain studded with knolls of glacial material; the river banks are deeply eroded, and some scattered small lochs are also present. The general aspect is north-westerly and the forest stretches on to the steep hills to the south and east.

The region is drained by the River Druie and its tributaries, the Luineag which flows out of Loch Morlich, and the Am Beanaidh out of Loch Einich. The general elevation of the main plain rises from about 225m near the Spey to about 360m as one proceeds southwards (Steven and Carisle 1959).

The underlying rocks over most of the forest are mica schists and siliceous granulites, but the higher ground to the south is on granite of the Cairngorm mass. North and north-west of Loch an Eilein, there are gneisses and schists with some crystalline white marble and calc-silicate rock, and here birch predominates. The soils, however, are derived mainly from glacial drifts, which over most of the forest are morainic in origin, but, particularly towards the River Spey, fluvio-glacial sands and gravels predominate.

The best groups of stands of pine are growing on freely drained sands and gravels while scattered trees of slowly growing pine are found on poorly drained soils with a thick layer of raw humus.

Over most of the forest Scots pine, Pinus silvestris, is the only tree species with an occasional birch particularly along the streams. On better soils North and North-west Loch an Eilein birches(Betula verrucosa, B. pubescens, or intermediate forms) predominate, together with a few aspen (Populus tremula), holly (Ilex aquifolium) and bird cherry (Prunus padus).

The forest is semi-natural and uneven-aged, with a predominance of older trees. There are groups of over 190 years old and ring counts gave a maximum age of 310 years. The most common age class, however, is between 180 and 120 years. There is a poorer representation of younger trees although regeneration under 20 years old is locally abundant. On the more poorly drained soils and at the higher altitudes, there are many small trees, no more than 9m high, which may nevertheless be over 150 years old (Steven and Carisle 1959).

The ground vegetation is dominated by Calluna vulgaris, Vaccinium myrtillus and V. vitis-idaea with subdominants Deschampsia flexuosa and Erica cinerea.

1.3. OBJECTIVES.

"The objectives to be achieved by the forest resource inventory is the most critical phase in the entire inventory process" (Frayer et al 1974).

To avoid unecessary effort a forest inventory should be designed to achieve clearly stated objectives which, in turn, should be precise, relevant and practicable taking account of the possible constraints.

The importance of the volume estimation has already been stated and in an extensive natural or semi-natural forest this undoubtedly requires the use of aerial photographs as a tool (section 2.22). Thus, the main objective of this study was to estimate the standing timber volume in Rothiemurchus Forest, which was chosen as an example of a semi-natural forest with relatively recent coverage by vertical aerial photographs. Due to limited time the study was restricted to Scots pine.

The objectives were set out as follows:

1. To identify Scots pine stands within a pine/birch mixture.
2. To stratify Scots pine stands on the basis of canopy closure and height class.
3. To find a relationship between crown diameter (cd)* and stem diameter at breast height (DBH)*.
4. To use (3); mean stratum height and an assumed form factor to estimate the preliminary standing crop volume from photo plots. This was to be carried out for selected

*Small letters are used for parameters measured on aerial photographs; capital letters for parameters measured in the field.

strata only due to limited time.

5. To collect field data to test the accuracy of estimated volume; the desired level of precision was defined as confidence limits less than or equal to 10 per cent of the mean volume per hectare.
6. To estimate the periodic mean annual basal area increment for the selected strata.

CHAPTER TWO

REVIEW OF THE LITERATURE.

Chapter two.

Review of the Literature.

2.1 INTRODUCTION.

The purpose of this review is to assess the value and limitations of vertical aerial photographs and to cover the essential information necessary to carry out photomensuration and photo-stratification to achieve the main objective of this study.

Photogrammetry and photo-interpretation are dealt with fully in Spurr (1960) and Howard (1970), and only those aspects of particular interest will be reviewed briefly. Aerial photographs will be described (Section 2.3) and how, as a tool, they are used to collect information for purposes of species identification (Section 2.51) and volume estimation (Section 2.4).

Due to the serious involvement of errors in forest inventories and due to their drastic effect on the final assessment, they must be identified and evaluated as far as possible, so that they can be eliminated or minimised. The errors which are involved in volume estimation are reviewed briefly in Section 2.632.

Timber volume estimation without increment assessment does not give a complete information for rational management decisions, and thus both must be estimated in order to complete the picture. Increment estimation requires a lot of time to be determined precisely in an extensive semi-natural forest; and so within the limited time available an effort was made to estimate increment within the survey area (Sections 2.64).

2.2 History, use and Limitations of Aerial Photographs.

2.21 History.

The detailed history of aerial photography is well covered by Howard (1970), but it is intended here to give a brief summary.

According to Howard the first aerial photographs reported in history were produced in France in 1826. Soon after that time development of the science of photogrammetry was begun. But inspite of the early development of basic ideas, practical application of aerial photogrammetry depended upon the development of other elements like the gelatin emulsion, the film and the aeroplane itself.

The extensive use of aerial photography started between 1916 and 1945 during which photo-interpretation was introduced and developed. Forest photo-interpretation has been used in some countries like Finland since 1945 and then gradually the advantage of truly vertical aerial photographs due to their relative simplicity for both mapping and interpretation has been recognised (Howard 1970).

2.22 Use and Limitations of Aerial Photographs.

The techniques of using aerial photographs for purposes of forest inventory have been developed over more than three decades. The aerial photograph provides an overall impression of the area and a richness of forestry detail which enables the interpreter to obtain information in the office with a greater ease and at lower cost than on the ground (Loetsch and Haller 1973a).

Photographs, of the proper specification, can be used in two different ways. First, by photogrammetric methods, maps may be constructed showing the distribution of physiographic units, vegetation and land use types. Secondly, through photo-interpretation, the photographs may be studied under a stereoscope and a variety of objects can be identified and measured.

The problem of surveying and map-making from photographs is complicated by the fact that the aerial photograph is a perspective and not an orthogonal drawing and therefore not a map. It is rather a picture distorted by topographic displacement, tilt and film and paper shrinkage. These causes of distortion will be discussed in some detail in Section 2.3.

As for the second use full details are given in Section 2.5.

By making the proper use of aerial photographic techniques, the amount of field work necessary in timber cruising can be greatly reduced and volumetric estimates of adequate accuracy may be prepared in a minimum of time and at a moderate cost. Photographic measurements alone are not sufficient to obtain volumetric estimates unless coupled with ground measurements which are required to determine allometric relationships. In addition more variables can be measured on the ground with greater precision. Aerial photographs, on the other hand, have two marked advantages in volume estimation:

1. Stand boundaries and stand areas may be accurately delineated and determined on photographs much more rapidly than they can be obtained by ground methods.
2. Samples and measurements may be obtained more rapidly on the photographs than on the ground. Statistical precision, therefore, may be obtained not by taking a limited number of carefully measured samples as in ground timber cruising,

but by taking a large number of samples on the photographs measured with only moderate accuracy (Spurr 1948).

An additional use of aerial photographs in inventory work is in controlling field work. They can be seen as an indispensable tool for the following reasons:

1. Stand maps developed from aerial photographs provide a highly effective means of stratifying a ground cruise. Plots may be located where they will make the maximum statistical contribution to the accuracy of the inventory estimate. With a fewer number of total plots than would be required for an uncontrolled cruise of the same degree of accuracy Section 2.614, a heavier sample can be taken in the higher volume, higher value, and more variable crop types; while the intensity of sampling can be reduced in the lower volume, lower value and more homogenous types.

2. The use of aerial photographs in the field permits the field parties to obtain their data with a maximum of efficiency. Non-productive areas may be left out; swamps and other areas of bad going may be bypassed; and much compass and pacing work may be eliminated. With photographs the field party can keep themselves constantly located and can choose the best route from one place to another. It should be remembered that the photograph is not an accurate map therefore it is as well to rely upon stand maps constructed from the photographs rather than the photographs themselves.

Another use of aerial photographs is site quality classification in terms of topographic location or species composition but not in direct terms of productive capacity of the soil.

In the following Sections more elaboration in the use of aerial photographs in forest stratification, identification of tree species, photomensuration and volume estimation will be reviewed.

Aerial photographs, however, do have some limitations which make field work inevitable to collect information which cannot be readily obtained from photographs even if they were produced in a high quality and of the correct specifications. These include stem diameter, stem quality, age and increment. Since the canopy obscures the ground surface and the ground vegetation, site assessment may only be limited to open stands and on clear areas.

On the other hand, stand volume estimated from aerial photographic measurements cannot be at any one location with the precision which can readily be secured by estimating from measurements taken on the ground. The high standard of error associated with the aerial estimate of stand volume as well as systematic errors which are likely to occur, limit the accuracy and the value of any single aerial estimate. Volume estimates from aerial photographs are therefore of limited usefulness in small accessible forest stands (Spurr 1960).

2.3 The Aerial Photograph.

In using aerial photographs, as with using any other tool, the first concern must be to select a tool of high quality in order to fit specific needs. By defining the objects of a forest inventory prior to flight, the specification of aerial photographs should be prescribed. This may include the scale and size required, film, filter, camera type and focal lengths etc., to be used so that most of the required information can be obtained.

The following review gives the general description of aerial photographs used in forest inventories.

2.31 Kind, size and other characteristic features:

Vertical aerial photographs, unlike obliques, can be studied stereoscopically (Section 2.4) to produce a three-dimensional image which helps more in photo-mensuration specially in tree height measurements. These are the kinds of photographs which are used widely in forest management work.

Oblique photographs, on the other hand, are more readily comprehensible than verticals as they present a more familiar picture, but because of the variation in the amount of distinguishable details within the obliques, and because of the difficulty of map preparation from them, they are of little use at present compared to the verticals.

Most aerial photographs are provided in the form of a contact paper prints made directly from the negative without the use of a projector and which are of the same scale as the negative. Prints made on film, glass or other transparent material may be viewed with transmitted rather than reflected light, they normally show finer detail and sharper definition than do paper prints. The positive transparencies should be used whenever the maximum amount of information is desired from photographs.

The normally used focal lengths vary between 152.4 mm (6") and 508 mm (20"). The size of prints used at the present time is 23 x 23 cm for which lenses of 152.4 mm focal length are most often used. The shorter the focal length the better is the stereoscopic effect for the same flying height but at the same time the distortion (i.e. image displacement) is increased. Short focal lengths are therefore especially suitable for determination of the contour lines and object heights. The image displacement and the stereoscopic effect are reduced if the flying height is increased for a given focal length (Howard 1970).

2.32 The Flight Map:-

Before executing the aerial photography, it is often necessary to prepare a flight map and it may also be necessary to establish ground control points.

A fundamental condition of flight planning is to provide adequate photographic coverage with the minimum number of photographs to satisfy the objective of the flight. The flight map of the area to be flown shows the boundaries of the area, the location of the starting and finishing photographs of each flight line and the location of the flight lines to one another and to important objects on the ground. To minimise the number of photographs taken, the flight lines should be arranged in the direction of the longest sides of the area (Howard 1970). Also the flight lines should be arranged so that high points are not near the edge of a photograph otherwise radial displacement will be exaggerated and be more difficult to correct during map preparation.

The flight lines are normally straight and continuous and are usually arranged parallel over the whole area. The interval between the lines is determined by the average contact scale and the prescribed amount of sidelap. In mountainous country sidelap may be increased and this is accompanied by an increase of the number of photographs, the cost of photography, evaluation and mapping.

The photographs are exposed along the flight line so that each successive photograph overlaps about 60 per cent of the field of the previous photograph. This large endlap is necessary to obtain a stereoscopic effect (Section 2.4).

2.33 Scale.

The scale of an aerial photograph is the ratio between corresponding distances on the photograph and on the ground, called the "representative fraction"(R.F.) This fraction equals the ratio of the focal length of the camera (f) to the flying height (H) above ground, i.e. RF = f/H where f and H have the same units.

The scale may vary within one photograph if the terrain is not perfectly level. It is, therefore, obvious that in mountainous countries, any measurement on the photograph requires the calculation of the scale of the particular locality on the photograph. This needs additional information on ground elevation. The scale can also be found by selecting a distance, preferably near the principal point, which can easily be recognised on the photograph and on the ground for measurement.

The scale of 1 : 5000 may be considered to be the largest practical scale for forestry interpretation. The most common scales are of the order of 1 : 10,000 to 1 : 20,000, but smaller scales of 1 : 30,000 to 1 : 50,000 taken with a wide angle lens, are often prefered for the compiling of the base maps and preliminary forest type maps.

2.34 Photographic Paper, Film and Filters:-

Thinner photographic paper is less stable under the influences of moisture and temperature. The shrinkage is 0.8 per cent for single - weight paper and only 0.12 per cent for double weight paper. Non-shrinking paper is available but expensive (Spurr 1960).

Photographic paper should not be too soft, as contrast is lost, nor excessively brilliant, because detail is lost. Generally glossy black and white paper is prefered, but occasionally semi-matt papers are used for special purposes. Glossy papers have the disadvantage that the reflection of light may produce a glare under the stereoscope and they are also less lasting and prone to crack.

The type of film and filter utilized will have an important bearing upon the value of the photographs for interpretation, Table 2.1.

Howard (1970) covers all the details about films and filters. The choice of the most suitable film material depends on the season. Panchromatic films and minus blue filters are used during summer in the temperate forests. Infra-red film and minus blue fulter are prefered in mixed hardwoods and conifers because this improves the distinction of the tree species. But in mixed deciduous forests panchromatic films are used during seasons when the deciduous forest is leafless, they are prefered to infra-red photography taken at a time when the deciduous forest is in leaf (Seely 1960).

Both types of film material have their specific advantages and the choice must depend on local conditions and the specific purpose of the photography.

Colour photography, however, is more expensive than black and white as well as having the disadvantages that it is affected by haze in the atmosphere and the resulting images on the photographic prints are generally not as sharp.

Table 2.1

Print characteristics produced from different film - filter combinations.

Film	Filter	Print characteristics
Panchromatic	Minus blue (yellow)	Give more detailed prints.
Infra-red	Deep red (cuts out other wavelengths except IR*)	Varied tone between hardwoods (appear in light tone) and softwoods (appear in dark tone).
Infra-red	Minus blue (allowing IR + visible)	Called modified IR photos which have the characteristics of the above two types and these are the most suitable for photomeasurements and tree species identification.
Colour		Colour photos, more expensive have limited resolution and poor tones - limited use e.g. detection of disease.

*IR = Infra - red.

2.35 Displacement on Single Photographs:

Displacement can either be caused by topography, aircraft (tilt)or the camera (optical and mechanical faults). The aerial photograph is produced in central projection while a map is an orthogonal projection. The map plane is either at sea level or at a chosen datum plane. The datum plane of an aerial photograph is correspondingly arbitrarily fixed. The differences of projection cause the displacement of points on the aerial photographs which are located above or below the map plane. This displacement occurs always along the line which connects the photo point and the nadir. It is, therefore, called "radial line displacement".

The exact location of the ground position of a photo-point is necessary for the ground check of the photo-interpretation. The calculation of the exact ground distance between a starting point and a photo-point is difficult if considerable differences of scale exist within the photograph. It is therefore necessary to determine the actual scale of the particular part of the aerial photograph.

A tilted position of the camera causes distortion on the photograph and consequently displacement of points. The displacement due to tilt is normally much less serious than that of relief because the amount of tilt is normally small.

The developments of optical technique have reduced the distortion caused by faulty lenses to such an extent that it can be neglected (Wood 1949).

2.4 Stereoscopic Study of Aerial Photographs.

Stereoscopic vision helps us to view an object simultaneously from two different perspectives to attain the mental impression of a three-dimensional image. In order to view stereoscopically two successive photographs on a flight line must be properly orientated, their principal and conjugate principal points must be clearly marked and they should be placed alongside with the area of the common overlap adjoining, otherwise a pseudo-scopic effect will result. The edges of the orientated photographs will only be parallel if the flight line is straight and if the photographs are free from crab and tilt.

The three-dimensional image produced by the stereoscope from the two-dimensional images of a stereoscopic pair, allows the interpreter to see much more detail than can be seen in a single two-dimensional photograph. On the other hand prolonged stereoscopic viewing causes fatigue which may reduce the three-dimensional effect, but this may be avoided by looking at distant objects through the window to release the eye strain.

2.5 Photo-interpretation of Forestry Details:

A forest inventory seeks to acquire information on the location, extent, composition and value of a forest resource to the accuracy required by the objectives of the survey. The interpreter will try to acquire as much of this information from aerial photographs as possible and to substitute photo-interpretation and photo-measurements for field work.

Photo-interpretation is a method by which features on the ground are recognised on aerial photographs on the basis of shape, dimension, tone, texture, pattern, location and association as seen on the photograph (Spurr 1960).

The information required from the aerial photographs should be clearly specified preferably before flight, because the amount of information on the aerial photograph depends to a large degree upon the photograph itself, the type of film and filter used, the condition of exposure, the season and time of day of photography and the scale.

Measurements on aerial photographs are made in order to facilitate interpretation and data collection. Height of trees plays an important role in the estimation of volumes, in stratification and in site classification.

Crown diameter, crown closure (crown cover) and crown counts can be measured satisfactorily on aerial photographs. Crown closure is a valuable measure of density.

Although the direct measurement of forest trees and stands is limited to height, crown diameter, crown closure and crown counts, these values may be related to other parameters to provide indirect estimates. Tree diameters, tree volume and stand volume have been estimated from measurements made on aerial photographs (Dawkins 1963, Dilworth 1959 and Seely 1960 respectively). Stem diameter is correlated directly with crown diameter which approaches a straight line in form (Hetherington 1967). Volume of trees and stands can also be estimated from height and crown measurements (Section 2.7).

2.51 Identification of Tree Species.

The identification of tree species plays a very important role in many forest inventories because of the often different utilization value of the various species and because of the different specific requirements with respect to climate, soil, plant association and silvicultural treatment.

The assessment area of a forest inventory is, therefore, often subdivided according to the range of the main tree species or of the more characteristic mixtures. Similarly, the growing stock is often subdivided according to the main timber species; Loetsch and Haller (1973a).

The identification of tree species has, therefore, two functions in forest inventory:

1. The subdivision of an assessment area into different strata, such as forest types;
2. The allocation of estimated standing volumes, or factors which contribute to the volume such as height, crown diameter,

number of trees, to tree species or groups of tree species.

It is obvious that the extent to which the aerial photograph can be used for the identification of species is a problem of great importance. Criteria for the identification of species include pictorial elements like shape, size, tone, texture, shadow, pattern and interpretive elements such as association with a particular site, Colwell (1954); Olson (1960). The application of tone scales for identification has its limitations because the tone of a given species in different crown positions is affected by shadows. Losee (1951) for instance found that the density grades influence the tone and may obscure the specific characteristics of the leaf reflection. Texture, on the other hand, is the aspect caused as a result of the coarseness of the crown or canopy. Smooth, velvety textures are commonly associated with young saplings, whereas coarse, cobbled textures usually indicate older trees. Some tree species have a specific texture caused by a characteristic branching habit. In plantations the different age classes have characteristic textures.

Sayn-Wittgenstein (1978) stresses the use of seasonal variations and inherent species characteristics (such as crown shape, branching habit) as key features for identification, since the desirable experience and knowledge of forest conditions are often lacking and the inherent indicators of species like topography, drainage, aspect and association may be unreliable.

2.52 Photostratification:

The purpose of stratification in forest inventories is to reduce the variation within each stratum by separating the area into more homogenous classes.

The main characteristics used for photostratification of forests are percentage crown closure,crown count, crown area or diameter and height. These characteristics could be used individually or in various combinations. Stratification based on these characteristics is important to forest management, because the characteristics are parameters of volume on which management is ultimately based.

Photostratification of the forest cover has many uses. Firstly, it defines forest associations that can be considered as a unit for volume sampling and management purposes. Secondly, it geographically locates these units and permits the estimation of their area for inventory purposes. Thirdly, it improves sampling efficiency by either reducing the sampling error for an equal sampling intensity or by reducing the sampling intensity for the same level of accuracy relative to a corresponding unstratified sample (HOward and Lanly 1975). In the latter case the amount of field work could be reduced by up to 60% (Spurr 1948). Such reduction is valuable in saving time and money. Finally photostratification helps to establish a sampling frame from which sampling units can be drawn objectively.

Besides the above uses, photostratification has many advantages which are well summarised by Spurr (1960).

Stratification can be carried out on aerial photographs with a scale of 1 = 50,000 and more effectively with scales of 1 = 20,000 and larger where stand height, density, crown diameters etc., can be measured easily for volume estimation (Hutchinson 1978).

It has been confirmed by many workers, like Maclean (1972), that stratification using aerial photographs is much cheaper than using ground methods alone. It follows that any stratification method could be used in the photostratification of a natural or sami-natural forest as long as the main objective of stratification is achieved, that is the improvement of sampling efficiency or the reduction of costs.

It is possible to transfer strata boundaries from aerial photographs to a base map using, for instance, a Sketchmaster, Section 2.531. A stand-class map would show area by volume class and would require continuous revision to be accurate. Such maps may be useful to the forest manager in many ways. They help identify areas approaching merchantability, and they indicate areas that should be examined for possible silvicultural treatment such as thinning and may also be useful in protection in order to combat a threat from fire or insects.

2.53 Maps from Aerial Photographs.

Aerial photographs are multiple-use tools in forest management. Their use in the construction of maps and in carrying out of forest surveys is obvious. In putting a forest under management, the first steps are to map it and to carry out a forest inventory. Since all forestry involves the management of land, maps showing the status and condition of land provide essential records upon which the practice of forestry is based.

Aerial photographs are found useful in the preparation of all types of maps. Stand boundaries and stand conditions can be recognised on good quality aerial photographs of the proper specifications and consequently stand maps can be prepared quickly and accurately (Spurr 1960).

2.531 Transfer of Stratum boundaries.

The Aero-Sketchmaster is used principally for transferring detail from aerial photographs (vertical or near vertical views) to maps by tracing. Photographs and maps are made to coincide by direct optical rectification. The essential element of the instrument is a double prism with a half-silvered face, which permits the user to view the photograph and the map sheet simultaneously through the oblique eyepieces. The photograph is fastened on a photo-holder which can be tilted and rotated in any direction. By doing this, and by changing the prism-photograph and prism-map distance relationships, the operator can see the photograph's image superimposed on, and in coincidence with, the corresponding points of the map, thus enabling him to trace out on the map the required details seen in the apparently superimposed image of the aerial photograph.

2.54 Measurement of Areas on Aerial photographs and maps:-

An outstanding value of aerial photographs is the ease and accuracy by which area determinations can be made (Spurr 1960).

The precision of area measurement depends upon (1) The accuracy of the photograph or map being measured and (2) the method of measurement adopted. If area measurements are made directly on photographs, errors may arise owing to variations in scale and slope. These errors may be minimised or avoided if area measurements are made on maps.

The scale of an aerial photograph is a function of the height of the camera above the ground and therefore varies with varying ground elevation. The lineal extent of scale change is directly proportional to the difference in elevation between the two scales being compared. For example photographs taken with a 6 - inch camera 8000 feet above a level plain, the scale at the ground elevation of the plain will be 1 = 16,000. On a ridge 800 feet higher than the plain, however, the scale will be 10% larger or 1 = 14,400. If the former scale is not corrected for this higher elevation, areas will be overestimated by 19% along the ridge (Spurr 1960).

Errors in area estimate due to variation in photograph scale are not likely to be important in flat country but scale should be taken into account in areas where the relief amounts to more than 3 or 4 percent of the flying height of the aeroplane.

In hilly country, slope is a major source of error. If the unit being measured slopes away from the principal point, its area will be underestimated; if it slopes toward the principal point, it will be overestimated.

Maps prepared from aerial photographs minimise or eliminate all the sources of error within the photographs themselves. It should be noted that the accuracy of detail on a map is dependent upon the means by which that detail is transfered to the map from the photographs.

2.541 Methods of area measurement:

Irregular area units can be estimated by using several methods and instruments like planimeters, grids, transects, the weight -

apportioning method and the photo-electric planimeter.

The various methods of area determination are each suited to particular types of work for instance the planimeter is both accurate and reliable in estimating areas of small units. Grids, particularly dot grids, provide a very rapid and reasonably accurate method of obtaining stand and strata areas in extensive surveys (Spurr 1960).

In its simplest form, the grid consists of intersecting lines forming rectangles or squares which are drafted onto the map or photograph or simply superimposed by means of a transparent overlay.

2.55 Photomensuration.

Forest mensuration in the field is mainly concerned with stem dimensions for volume estimation. On aerial photographs, however, the canopy is the main source of direct information. Consequently, photomensuration is often concerned with height and crown measurements usually crown diameter (cd) and crown area (ca) which are measured directly on aerial photographs for volume estimation. Since the main volume estimator measured in the field, diameter at breast height (DBH), is not measurable on aerial photographs, statistical relationships are often sought between photomensuration parameters and field mensuration parameters.

In the following review tree heights and crown measurements on aerial photographs are dealt with.

2.551 The measurement of tree height.

The height of trees plays an important role in the estimation of volumes, in stratification and in the classification of sites. Therefore the accuracy with which height can be measured on aerial photographs greatly affects the accuracy of the calculated volume. Tree height can only be measured when the tree top and the ground are visible. There are two main methods of height measurement on aerial photographs namely the shadow method and the parallax method.

The first method use the following formula:

$$h = l . \frac{1}{RF} \tan \alpha$$

where h = tree height

l = measured length of shadow on the aerial photograph

RF = the representative fraction

α = the angle of the elevation of the sun.

This method requires the following conditions: the shadow must be on level ground and not be shortened or lengthened by a slope; the whole length of the shadow must be clearly visible and not be distorted or obscured by undergrowth or by neighbouring trees. The angle of elevation of the sun and the photo scale at the point of measurement are also required.

The second method is the most satisfactory one in measuring tree heights for stratification and photo volume estimation (Loetsch and Haller 1973a). The usual parallax formula applied is as follows:

$$h = \frac{Hi . dp}{B + dp}$$

where h = the height of the tree.

Hi = the height of the aeroplane above the base of the tree.

dp = the parallax difference

B = the absolute x-parallax.

The flying height (Hi) must be in the same unit as the tree height (h), while B and dp can be in a different unit.

The main disadvantage of this method is that considerable experience is necessary to achieve an adequate accuracy and reliability of work.

The determination of tree height or stand height plays an important part in most systems of aerial volume determination, and the accuracy with which height can be measured on photographs, greatly affects the accuracy of the calculated volume.

It has been stated that a difference of five feet in the height of a mature tree will in some instances double the calculated volume of the tree (Sammi 1953).

It is clear that without a thorough knowledge of the systematic (non compensating) as well as the accidental (compensating) errors of height measurement, volume estimates based on such measurements cannot be properly evaluated.

Systematic errors can be corrected by means of general correction tables for the different crown shapes and scales (Worley and Landis 1954); chance errors can be reduced by making sufficient number of measurements to reduce the standard error of the height of the mean stem.

2.552 Crown Measurements.

As crown diameter (cd) can be well correlated with diameter at breast height (DBH), (Dawkins 1963), this shows it is clearly important in volume estimation.

Measurements of cd on aerial photographs are usually underestimated because they do not include branches hidden by neighbouring trees and branches which are too thin to be resolved. Hence the term "visible" crown is given to the crowns which are resolved or appear on the photograph.

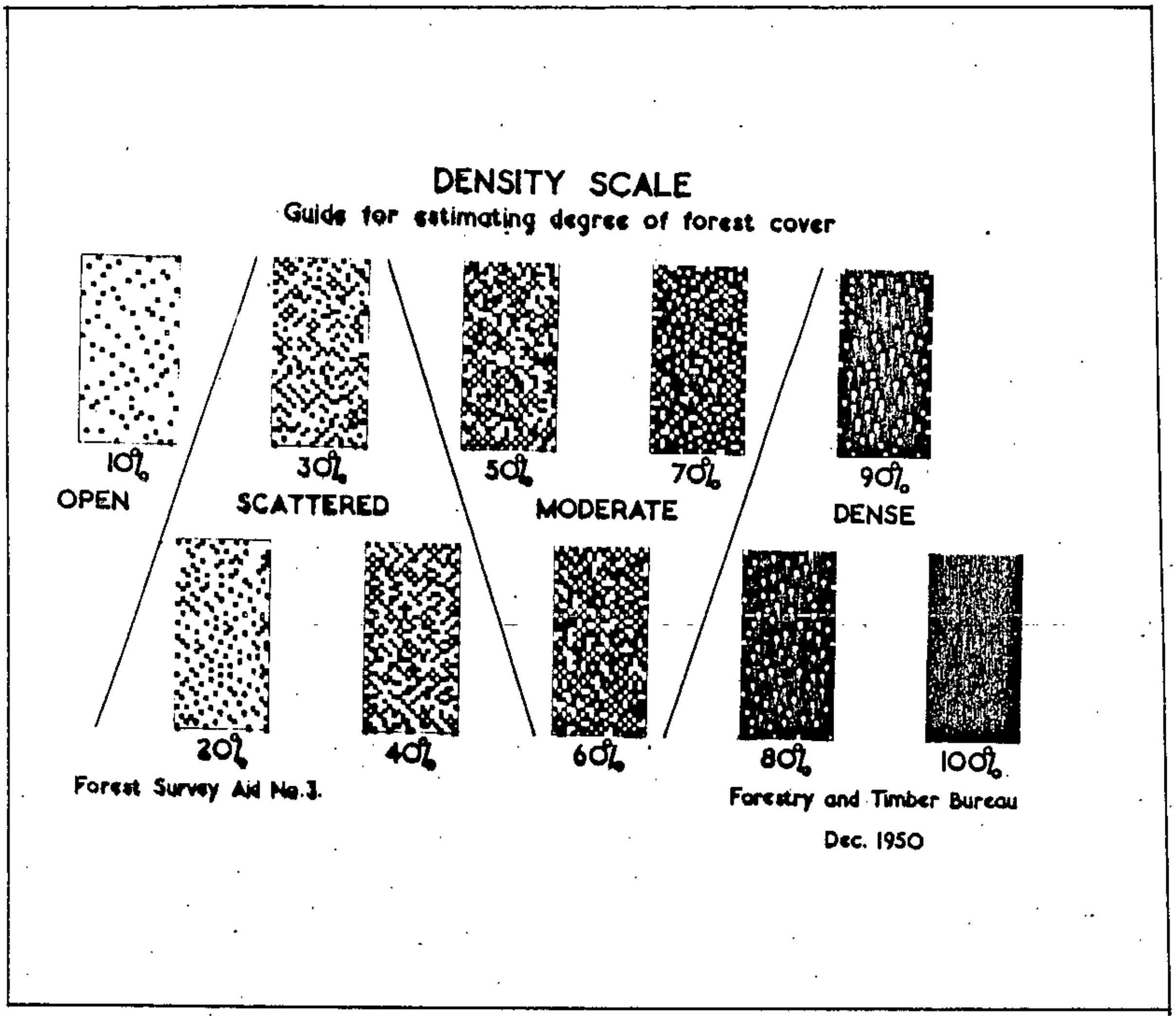
There are four devices used for measuring crown diameter namely the crown wedge, the spot gauge, micro-dot template and magnifying scale. The crown wedge is easier and quicker to use as well as giving precise measurements due to the stereoscopic view of the trees (Howard 1970).

In dense stands it is easier to measure crown diameter than tree height. The main difficulty is that crowns of several adjacent trees may appear as one large crown; this problem can only be resolved by ground checks.

2.553 Crown counts and Crown closure measurement:

Stand density can either be estimated in terms of crown closure or in terms of the number of tree crowns visible on the aerial photograph. By using the latter method it is possible to obtain a single numerical value of density which is relatively free from the factor of personal judgement. More accurate counts can be made in less dense stands. The disadvantages of crown counts are the difficulty of getting an accurate count

FIGURE 2.1 : Density scale (Moessner 1949).



and on the poor correlation between crown count and stand volume (Spurr 1948)

Crown closure (crown cover), on the other hand, is an essential guide in estimating the volume from aerial photographs (Pope 1961). It can be estimated visually by comparison with certain standards. Moessner (1949) has produced a crown density scale, which is widely used because of its simple and practical design, Figure 2.1. As only the "visible" crowns were measured, the crown cover was expected to be underestimated. Moreover, a number of factors bias the estimate of crown closure especially when using a crown density scale. Shadows for instance can often result in over-estimation of crown closure on slopes facing away from the sun. Another source of bias is the displacement of the crowns which appear larger as the distance from the nadir increases. The use of correction tables can reduce the bias due to these sources.

2.6 Timber Volume and Increment Estimation.

2.61 Sampling techniques.

The precision of a volume or growth estimate is controlled not only by the accuracy of the measurements of trees and stands but also by the fact that it is impractical to measure all the trees for which the estimate is desired.

A saving of money is the most common reason for sampling, but a saving of time is sometimes more important. Furthermore, sampling may be more accurate than complete enumeration since fatigue contributes substantially to measurement errors. On the other hand, by considering tradeoffs between costs and precision of the information derived, sampling error can be controlled to a required degree, or to the limit of the budget resources.

Thus sampling must be carried out as an integral part of the forest inventory procedure.

2.611 Double Stratified Sampling.

The strata are defined in such a way that the least variation is found within strata, and each stratum is sampled separately by random methods.

In an illustration, Schumacher and Chapman (1942) showed that one stratified sample is equivalent to eight unstratified samples. Bickford (1961) commented that more than five times as many ground plots would have been needed without strata, and concluded that it is more efficient to purchase the photography, for stratification, than to rely solely on ground plots.

The application of double sampling to tree populations was described by Bickford (1952) and the theory is well explained by Cox (1952) and Cochran (1963).

The term double sampling comes from the fact that some of the elements selected for the sample are measured twice. The larger sample is usually obtained at less cost per unit, as from aerial photographs, but it is not as accurate as the smaller or the subsample which is more costly, usually field measurements. Thus the accuracy of field measurements can be combined with the economy of photo measurements, and by using a regression relationship the bias can be removed from all the photo measurements.

Volume estimates can be made on photographs but should be checked by ground measurements. Double sampling provides the means for accomplishing this and for obtaining a single volume estimate based upon both the photographic and the field information.

Two useful tools of double sampling are the separate calculations of the correlation coefficient and of the regression between data from the photographic sample plots and from the same plots in the field.

2.612 Sample intensity; plot size and shape:

The basis of representative sampling of a forest area is the premise that investigations and measurements of a portion of the survey area are applicable to the whole forest. Since only a given proportion of forest area is sampled, the total volume is not known exactly, but estimated within certain ranges of accuracy by statistical methods. The accuracy of the estimate is dependent on the intensity of sampling and the variation within the forest.

Barton and Stott (1946) have prepared a pictorial chart in order to present a simple guide for determining the required sampling intensity corresponding to a certain degree of accuracy. The chart gives the number of 1/5 acre sample plots needed for attaining different levels of accuracy in stands of different degrees of uniformity and density. The chart is based on certain numerical values of the coefficient of variation of the volume per sample plot characteristic for various stand conditions. The problem of correctly identifying the actual stand conditions with any one of the particular categories included in the chart, presents a difficulty in using the chart.

Meyer (1949) noted that a number of other factors besides stand uniformity and density greatly affect the variation in volume from one sampling unit to another. Such factors are: size and shape of sampling units and efficiency of sampling design. An efficient design obtained by sub-dividing an area into blocks of relatively homogenous stand conditions (stratification) or by laying strips or cruise lines at right angles across the main stand stratification, will lead to considerably smaller coefficients of variation. It therefore appears that correct appraisal of the sampling intensity required for a certain degree of accuracy can be made only if the standard error of a cruise in a given forest type and for a given sampling method has actually been determined.

To determine the number of plots that are required to achieve a desired precision the following formulae are used: (OAS 1969):-

(1) $$n = \frac{S^2 \cdot t^2}{E^2 + \frac{t^2 \cdot S^2}{N}}$$ For small areas - (limited population).

(2) $$n = \frac{S^2}{\frac{(E)^2}{(t)^2}}$$ For large areas - (Unlimited population).

where n = number of sample plots

s = standard deviation

S^2 = variance

E = Allowable error.

t = normal deviation

If n is large - (t = 1 for 67% probability
(t = 2 for 95% probability

N = Number of sampling units possible = total forest type area divided by plot size, expressed as a fraction.

The Standard deviation (S) represents the relative variation of individual plot volumes. It has very little use in comparisons between inventories or sample methods. More information on the comparative dispersion of the sample population is obtained from the coefficient of variation (CV), which is most commonly used in showing the variability with in a forest unit or other population to be examined.

The coefficient of variation for a total forest is much larger than for individual forest types. The delineation of forest types on aerial photographs allows consideration of the individual types as a separate population to be sampled. This allows the more valuable types to be intensively sampled to estimate volume more accurately (OAS 1969).

Forest experience was used to calculate numbers of photo plots and ground plots and the distribution of the latter by Strata (Bickford 1961; Hetherington 1975).

The general principles underlying the intensity of ground sampling of any one stand class are that in general, classes having the largest volume per unit area, the greatest commercial value, and the most heterogenous structure should be sampled most intensively, whereas low volume, low value, homogeneous classes need be sampled only lightly.

Because so many considerations enter into the determination of how many field plots should be established in each forest stratum, a variety of approaches to the problem have been devised. These fall into two general groups:-

First: The number of plots is determined by the variation within the class, either through the use of standard statistical formula or through arbitrary rules based on statistical knowledge of the forest types.

Second: The number of plots is fixed by economic considerations, but this fixed number is distributed among the various strata to achieve an efficient forest survey (Spurr 1960).

Circular plots are prefered in photo-sampling, but the choice of size depends on the scale of the photograph and on the character of the sampled forest. If the photo plots are very large, errors of counting or of measuring can be expected. Smaller plots, on the other hand, have more doubtful borderline cases. A rule of thumb is that a plot, for counting or measuring crown diameters, should contain no less than 10 trees and no more than 30 visible trees (Loetsch and Haller 1973a).

The scale variation must be considered in hilly country, either by varying the photo-plot size or by adjusting the sample plot ground area.

2.62 The Tree Aerial Volume Tables.

Tree aerial volume tables are based mainly on the regression stem diameter on crown diameter. More satisfactory, however, is to prepare proper tree aerial volume tables by accurately locating plots both on the photographs and on the ground. Investigations of this kind have been described by Nash (1948), Ferree (1953), Dilworth (1959) and Loetsch and Haller (1973a). As it is very difficult to locate accurately individual trees both on the photographs and on the ground specially in very dense stands, the tree volume table construction is not considered in this study.

2.63 Stand Aerial Volume Tables and the estimation of Volume:-

As the use of single tree volume tables in air-photo-interpretation is restricted to conditions in which a favourable stand structure permits reliable distinction of single trees for measurement, many workers have investigated the possibilities of obtaining area-related independant variables from aerial photographs which are sufficiently related to the total volume.

The two chief independent variables for volume regression in ground inventories are "the basal area per unit area" and "the mean stand height". Only the stand height can be directly measured on aerial photographs while the basal area must be substituted by the crown closure per cent.

Usually the scale of the aerial photographs affects the estimation of the independant variables, for example small scales below say 1 : 20,000 may result in low accuracy.

Data are measured from a sufficient number of exactly corresponding photo and ground plots and the table is then constructed by means of multiple regression analysis. Two types of difficulty arise in the collection of data for the construction of stand aerial volume tables. Firstly the difficulty of locating the plots on exactly corresponding points on the ground and on the photograph, Secondly the difficulty in preventing biased errors caused by the subjectivity of the interpreter.

The first difficulty is more easily overcome if the photography is flown as part of the inventory. The plots can be marked on the ground before the photography in order to be recognised on the photographs (Loetsch and Haller 1973a). But since one of the major uses of aerial photographs is stratification and consequently selection of photo followed by field plots, marking of plots before photography may not represent the population to be examined and a serious bias may be made, so it may be convenient to put some marks systematically before photography which may serve later to locate field plots. These marks may be specially important in extensive flat areas where they lack characteristic features like rivers, buildings, roads etc. If existing aerial photographs are used in a forest inventory, as in the present study, the necessary accurate location of the plots on the ground is an important problem. The smaller the size of the plots, the greater must be the accuracy of locating the plot centres both on the photographs and on the ground. Conspicuous topographical features can be used to locate the position of two points on the photograph and in the field. These two points can then be used to locate the sample plot positions.

The plots for the construction of a stand aerial volume table are preferably purposively selected. Since the table will be constructed by means of a regression analysis, the whole range from low to high volumes should be covered by an adequate number of plots.

The second difficulty, which is the individual bias, can be dealt with by proper training and by the use of correctly calibrated instruments (Hetherington 1975).

An example of the construction of a stand aerial volume table is the table for upland oak in central Pennsylvania by Gingrich and Meyer (1955).

The stand aerial volume tables are used for the following purposes:-

1. For volume estimation in pure photo-sampling, which may be

checked by ground control.

2. For the assessment of relative volume classes as basis for stratification.

3. For the estimation of the coefficient of variation prior to the planning of the ground sampling.

2.631 Limitations of a Stand Aerial Volume Table (SAVT).

There are mainly four limitations which can be summarised as follows:-

1. The table (SAVT) normally gives only the gross round wood volume. Size class distribution, timber quality, age, increment (and often also species) can only be obtained from ground measurements.

2. The use of SAVT requires a high degree of specialisation. A minimum of two months is needed to train an interpreter and a year or more is advisable for an estimator, Moessner (1960).

3. Regional volume tables require adjusting if used locally. This reduces the precision of the results and thereby the value of the information obtained (Loetsch and Haller 1973a).

4. According to Meyer and Worley (1957) it is generally preferable to survey small forests with a small coefficient of variation by a pure ground inventory. The volume estimation from SAVT is practical and economical only for large areas.

The chief advantage of SAVT, however, is the saving of time in that ~~many~~ photo plots can more easily and rapidly be measured than ~~the same number of~~ ground plots. Furthermore inaccessible areas can be sampled without much difficulty; photo-estimates can be made during the off-season in which field work is impeded by adverse climatic conditions.

2.64 Sources and estimation of error:

Usually, error means the deviation from the true value. Inaccurate measurement or estimation implies that an error is associated. Inaccuracy may be due to the following:-

a. Irregularities of the object to be measured, the more the shape is geometrically regular and the boundaries are consistent, the more accurate will be the measurement.

b. Inaccuracy of the measuring device.

c. Environmental influences, for example changes of temperature may produce deformations on measuring devices; sight is impeded by rain and thus measurements carried out under different weather conditions yield deviating results.

d. Uncertainties in the measuring procedure, as a rule every measuring operation comprises a certain error margin. Errors resulting from formation of classes and rounding off, belong to this category.

e. Imperfection of human senses.

The accuracy of forest inventory measurements normally depends on a mixture of several sources of error and it is often difficult to analyse the various components of the total error to their sources, or to calculate the total error from its different components (Loetsch and Haller 1973a).

The various sources of error which affect the accuracy of an aerial photographic inventory are:

1. Errors of measurements.
2. Sampling error of selected plots.
3. Errors of estimates of aerial stand volume table.

1. Generally the errors of measurement on ground or on photographs are of three kinds:-

a. Unilateral errors of regular magnitude, called systematic or one-sided errors.

b. Bilateral errors of random magnitude, called the random errors.

c. Unilateral errors of random magnitude, called one-sided random errors (Loetsch and Haller 1973a).

These three kinds of measurement errors generally occur in combined form. Systematic and random errors are quite different in the way they affect the result of measurement. Systematic errors of constant magnitude accumulate continually and increase with the increase of number of measurements, while random errors approaches zero.

Measurement errors occur to some degree because of instrumentation limits or human errors in recording data. The first can be measured and can also be minimised by selection of appropriate measurement equipment. The second, or human errors, are very difficult to evaluate for example errors can be made in taking readings, recording data, transfering data and summarisation and possibly some items might be omitted completely. They can be, however, controlled to some degree by selection of who is to make measurements, the training given and the environment in which they work are considered. Also resampling and field checking of measurements can help to estimate and reduce these errors. Sampling also help to minimise measurement errors considerably. Recently, methods of data logging in the field e.g. solid state recorders, are used in order to eliminate human errors completely.

2. Sampling error occurs because only part of the population is measured. It is usually measured by the standard error of the estimate and it is a function of sample size and can be influenced by shape and size of the sample plots (Hetherington 1975).

In forest volume surveys, sampling errors of 5%, 10%, 15% and 20% of the mean are commonly used (Howard 1970), but in general it should be one third or less of the total inventory error.

3. The error of estimate of the aerial stand volume table is independent of the errors of photo measurements and is due to differences in forest stands which are characterised by the same height and crown cover per cent (Gingrich and Meyer 1955).

As a result, the total error in estimating plot volume includes both the error due to photo measurement and the error of estimate of the volume table:

$$E_T = \sqrt{E_m^2 + E_e^2}$$

where E_T = Total standard error of calculated plot volume.

E_m = Standard error of plot volume due to errors of measurement.

E_e = Standard error of plot volume due to error of estimate from the regression line.

All error components can be controlled to some degree. However, increased accuracy and precision are associated with higher costs and therefore economic considerations must be linked with the level of error desired or afforded in a measurement system.

2.65 Estimation of Increment.

One of the objectives of intensive forestry to aim at is to maintain the highest possible increment from the forest area under management. If several periodic inventories have been carried out, the trend of the change in volume often provides sufficient information for further planning of the annual cut. The annual increment also plays an important role, for instance, in the determination of the time of felling of older stands.

There are many factors which affect the increment of a tree or the stand. These are the genetic constituents of the tree, age, site and the position of the tree within the stand.

The main types of increment include volume, basal area and height increment. With reference to time interval of observation there are three types of increment:-

1. The current annual increment (CAI), refers to the growth in the current year.
2. The periodic mean annual increment (PMAI), of a tree or a stand which is the mean increment over a period of (commonly) five to ten years.
3. The mean annual increment (MAI) which is the total production to date divided by age.

CHAPTER THREE

METHODS OF WORK INVESTIGATION

CHAPTER 3.

Methods of Work Investigation.

3.1 The aerial photographs used:-

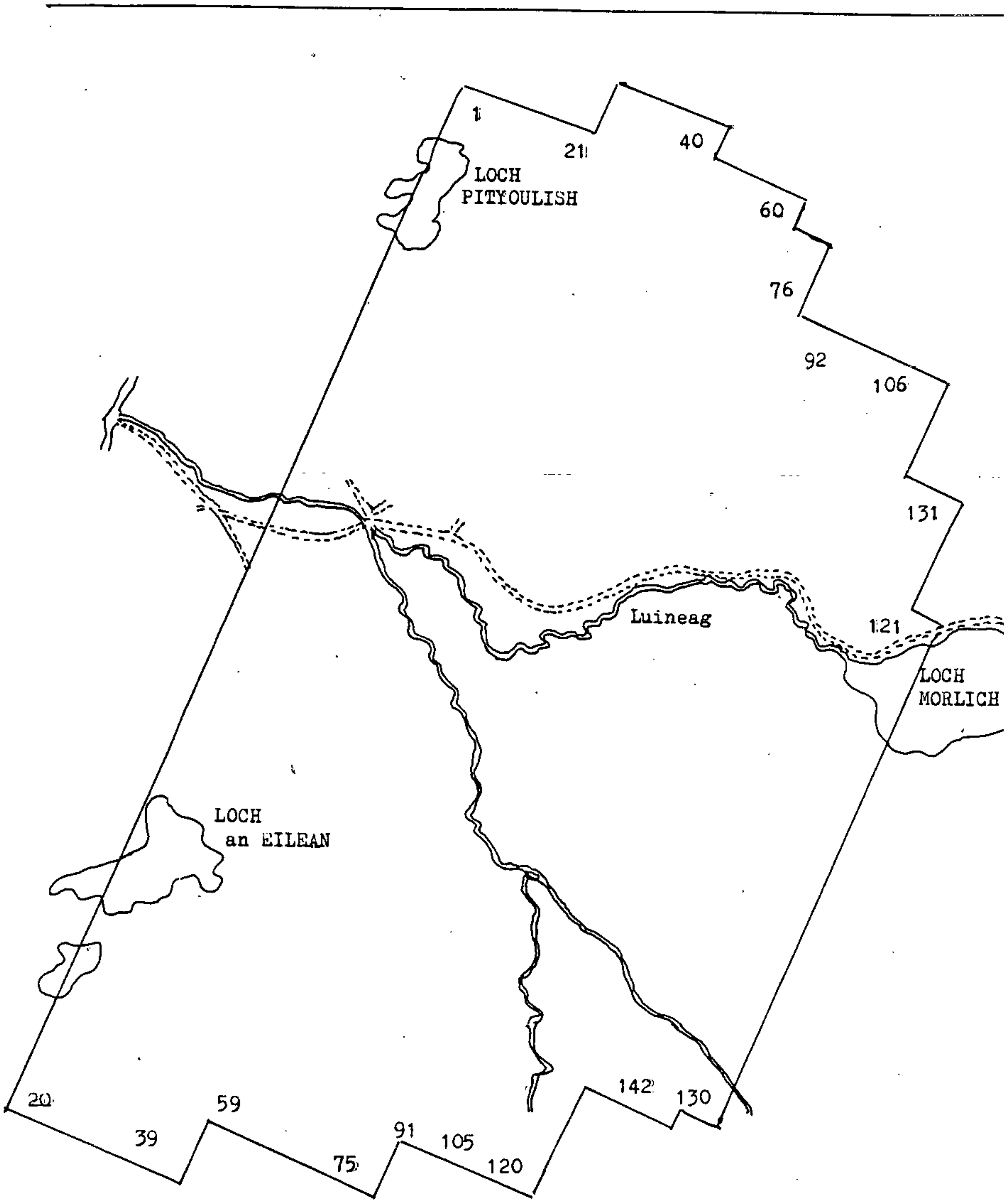
No prescription for aerial photographs were made for this study because the survey area was already covered with recent vertical aerial photographs which were used to achieve the set objectives. The flight map for the above mentioned photographs is shown in Figure 3.1.

The characteristics of the aerial photographs used throughout this work were as follows:-

Area	=	Rothiemurchus Forest (Section 1.2)
Contractor	=	Cambridge University.
Sortie/Prints	=	RC8 - Cu 1 - 142.
Date and time	=	29/7/1978, Afternoon G.M.T.
Camera	=	Wild RC8
Lens	=	152.75 mm.
View	=	Vertical
Mean negative scale	=	1 : 5000
Film	=	Panchromatic
Filter	=	Minus blue.
Prints	=	Glossy contact prints on paper.
Format	=	23 x 23 cm (or 9" x 9").

All the photographs, free from crab, were examined (in stereo pairs) under a Hilgar and Watts Stereoscope fitted with a parallel guidance mechanism and X4 binoculars. The purpose of this stereoscopic examination was to distinguish the woodland types

FIGURE 3.1 : THE FLIGHT PLAN FOR THE SURVEY AREA.



on the basis of species and their density and to measure tree heights and crown diameters.

3.2 Identification of Species.

The general reasons for species identification were discussed in Section 2.51, but in this study it is intended to distinguish between pine and birch specially in mixed stands in order to work out the density of pine separately so that its volume ~~will~~ can be estimated.

The survey area is mainly dominated with Scots pine and birch, Section 1.1, other tree species are also present but in ~~an~~ insignificant amounts, like Sitka spruce, Larch and Juniper scattered very sparsely among the semi-natural woodland. Because of the insignificance of these latter species and because they do not provide enough ground checks to be compared with their images on the photographs, they were consequently not considered. Thus identification of tree species was restricted only to the two major species Scots pine and birch, and since these species belong to two different groups, conifers and broad-leaved respectively, it was difficult~~y~~ ~~was~~ encountered to distinguish them on prints produced from a panchromatic film and a minus blue filter. The most difficult situation is where there is a mixture of young pine and birch. The most ideal prints, however, for the identification of these two groups should be produced from an infra-red film with a minus blue filter (Section 2.51). Inspite of the above difficulties, however, some criteria for identification can be distinguished. In the very old scattered mixed stands of pine and birch, the two species can easily be distinguished by means of tone and texture.

Birch trees appear to have light tone and fine texture while the pine trees have a slightly darker tone and a coarse texture. This conclusion was reached after a field visit when both birch trees and pine trees were identified on the photographs and compared. The information was then spread to the rest of the area using the photographs. In pure dense stands of the two species tone and texture were also used for identification, a pure stand of birch shows a lighter tone and a finer texture than a pine stand. Species identification using the appearance of the trees (Sayn-Wittgenstein 1978) was not tried in the survey area due to limited time.

3.3 Density Determination.

Density determination and stratification of the survey area started first by making a rough mosaic of the whole area covered by aerial photographs by laying down alternate prints, which was then examined in order to note the overall distribution of the woodland and the quality of the cover. This was then followed by examining stereo-pairs, taking prints of each flight line in turn, under a stereoscope. During examination of the stereo-pairs, areas having similar tones, textures and similar density patterns regardless of height at first, were delineated. Non-forest areas whether moorland or farms as well as regeneration areas whether artificially or naturally established were also delineated on the photographs using wax pencils.

The purpose of this initial step was to distinguish a series of stand types on the basis of their density and species. Since Scots pine is the dominant species in the survey area and because of the time limit only the pine stands (pure and mixed) were considered for density determination.

The method of density classification was based on that of I. Langdale-Brown and Garwood (1977) with some modifications to suit the objectives of the inventory.

The three-category density classification of Langdale-Brown and Garwood was as in Table 3.1.

Table 3.1: Langdale-Brown and Garwood Density classification

Class	Description	Maximum Cover %	Minimum Cover %
1. Dense Woodland	Continuous canopy few if any gaps	100	70
2. Open Woodland	Ground visible between clumps of trees some of which are extensive	70	20
3. Scattered trees	Separate trees often widely spaced, only occasional clumps	20	<5

This classification was modified into six density categories, in order to provide more accurate volume estimates (Table 3.2).

Table 3.2: The modified density classification:

Class	Maximum cover %	Minimum cover %	Class symbol
Dense Woodland	100	80	1
	80	60	2
Open Woodland	60	40	3
	40	20	4
Scattered trees	20	5	5
Moorland	5	zero	N

This classification of crown cover per cent was used in the survey area, as will be seen later, and each of the areas classified was labelled accordingly. The letter "N" denotes no trees which comprises cultivated land and wet or dry moorland; the letter "R" was also used for areas of regeneration, whether natural or artificial, with crown diameters on photos below 0.03 cm i.e.trees with DBHS below 7 cm.

After the completion of the preliminary delineation the crown density scale (described in Section 2.553) was used to estimate the crown cover per cent of stands under the stereoscope. The scale which consists of a series of transparencies with patterns of randomly distributed black squares covering from 10 to 100 per cent of the surface area (with 10 per cent intervals) Figure 2.1.

Due to the variability of crown sizes in different stands, several sets of crown density scales were produced by enlarging and reducing the original so that the sizes of the squares should roughly be equal to the size of crowns in order to allow for better density comparisons.

Having selected the right scale for a particular stand, it was then compared with the density of the stand under the stereoscope. Transparencies of different density were then tried until one matched the crown cover of the stand; this was taken to be the estimate of crown cover of the stand which was then marked on the photograph.

The crown cover per cent for all the stands was estimated by the above method.

3.4 Height Determination and Stratification.

Height measurements in each delineated stand (Section 3.3) started after the completion of the density classification.

Since the conditions required to measure tree height by the shadow method (Section 2.551) could not be met in the survey area, this method was not used. Consequently the parallax method, with a light floating dot, was used. Before its use, almost six weeks were spent in practicing and producing reliable results.

On the photographs of the survey area sufficient height measurements for stands or photo plot height were made until the last five measurements agreed within zero to 2.0 metres precision and the mean was then found for the stand or plot height. This may reduce chance errors considerably.

The trees for height measurement were selected so that the ground level near the base of the trees was visible in order to facilitate accurate measurements. The main difficulty encountered is in dense stands where the ground level ~~is~~ was not visible to allow correct parallax reading at ground level. In these cases edge trees were measured where ground level was visible since the floating dot will have no access to ground level in such stands. Measuring edge trees may overestimate the stand height as they are usually taller than inner trees. These will be corrected during field measurements (Section 3.8).

The parallax formula in Section 2.551 was used to calculate the heights. Due to limited time the heights of only seven trees were measured in the survey area, by the parallax method as well as on the ground in order to test the accuracy of the floating dot method before the main measurements (Table 3.3).

Table 3.3 Test of accuracy of height measurement, using parallex method, for the survey area.

Tree No.	Parallax heighting m	Ground height measurements m	Error
1	8.23	10.0	-1.77
2	11.04	12.5	-1.46
3	7.29	9.0	-1.71
4	12.54	13.0	-0.46
5	9.38	8.5	+0.88
6	11.20	10.5	+0.70
7	13.92	14.5	-0.58

It can be concluded that tree height is underestimated on the photographs compared to field measurements and this is attributed to lack of image resolution, as the small leading tip and other small vertical branches were not fully resolved on the photographs.

After measurements of field plots (Section 3.8), heights in photo plots corresponding to field plots were measured and means were found which were compared with mean heights of field plots as in Table 3.4. If the trees in photo plots are dense, height measurements were made at the nearest gap or edge of the stand.

Density and height were selected as criteria for stratification since both can be measured on the aerial photographs. Five density classes were recognised as explained in Section 3.3 and six height classes were established with an interval of 3 m as follows:-

Table 3.4 Comparison of height measurements in photo plots and in corresponding field plots.

Stratum	Occ. No.	Plot No.	Photo Ht. m.	Ground Ht. m.	Error
1d	8	9	13.01	11.11	+1.9
"	8	16	15.99	12.46	+3.53
"	8	11	15.27	14.91	+0.36
"	20	2	15.41	14.97	+0.44
"	20	3	16.18	18.08	-1.90
2d	12	1	12.71	12.12	+0.59
"	13	1	12.19	10.75	+1.44
"	2	1	16.41	17.55	-1.14
"	2	2	14.51	15.00	-0.49
"	9	2	14.93	12.88	+2.02
3d	11	6	14.67	14.56	+0.11
"	11	4	19.11	18.45	+0.64
"	13	1	14.88	14.33	+0.55
"	3	6	15.18	16.56	-1.38
"	8	13	14.08	12.83	+1.25
"	15	1	10.96	12.45	-1.49
"	10	1	15.43	16.78	-1.35
4d	1	8	14.14	14.58	-0.44
"	15	2	15.02	16.67	-1.65
"	7	1	10.12	9.00	+1.12
"	4	5	12.29	11.95	+0.34
"	9	1	13.95	11.86	+2.09
"	10	1	11.67	11.25	+0.42
5d	1	8	15.05	14.23	+0.82
"	17	1	12.95	12.63	+0.32
"	6	1	9.72	9.44	+0.28
"	13	1	13.77	12.13	+1.64
"	25	7	15.48	15.75	-0.27
"	25	5	12.09	12.90	-0.81
"	25	1	11.01	10.78	+0.23
1f	8	1	19.18	20.41	-1.23
"	1	4	15.94	17.35	-1.41
"	1	12	21.10	18.08	+3.02
"	1	7	20.98	19.08	+1.90
"	12	7	21.55	17.75	+3.80

Mean error = $\frac{+15.25}{35} = \underline{\underline{+\ 0.44}}$

Ht. class	Class symbol.
4-6	a
7-9	b
10-12	c
13-15	d
16-18	e
19-21	f

Knowing from measurements that total height will not exceed 21 m and that trees with heights less than 4 m contribute little to standing volume.

The density and height classes were then combined in Table 3.5 to form 30 strata all of which were identified on the aerial photographs and their boundaries ~~are~~ were made clear so as to be transfered to a map, Section 3.5.

Normally the ground height measurements is greater than the photographic "visible" height measurements (Table 3.3). In Table 3.4 it can be observed that a considerable number of photographic height measurements are higher than the ground ones and this may be attributed to selection of trees for measurement, with visible top and base near the photo plots on the photographs; these trees usually grow near gaps or at the edge of the stand and consequently are taller than inner trees.

Since the photographs are four years old, Section 3.1, tree heights should increase within this period considerably especially young trees, but since measurements for this study were made ~~to~~ on mature trees, height increase for such trees may not be appreciable.

Table 3.5 Stratification.

Density classes (per cent crown cover)	Symbol	a 4-6	b 7-9	c 10-12	d 13-15	d 16-18	f 19-21
		Height classes (met~~er~~res).					
100 - 80	1	1a	1b	1c	1d	1e	1f
80 - 60	2	2a	2b	2c	2d	2e	2f
60 - 40	3	3a	3b	3c	3d	3e	3f
40 - 20	4	4a	4b	4c	4d	4e	4f
20 - 5	5	5a	5b	5c	5d	5e	5f
5 - 0	N						

3.5 Transference of Strata boundaries and Area Measurements:

The strata, as explained in Section 3.4, were transfered onto a base map of scale 1 : 10 000 in order to make field work and location of field plots easier and to help in further forest inventories and in forest management plans.

The Sketchmaster (Section 2.531) was used for transfering the strata boundaries to the map by tracing. Photographs of each flight line were taken in turn in order to make the work easier and systematic. Obvious features on the photographs and on the map were superimposed first, e.g. roads, rivers, buildings etc., then followed by tracing the strata boundaries on the map and each stratum was given its label e.g. 1a, 2a, 2d, 3f etc., map in appendix K.

Difficulties arose in matching and superimposing areas in steep mountainous areas, as in eastern part of the survey area, but by working from obvious superimposed features at both ends and working towards the sloping area, gave satisfactory results.

The areas of all the thirty strata were then measured on the prepared map by using a dot grid made on a transparent overlay. The overlay was placed over an occurence of a stratum, and the rectangles and dots were counted, taking the mean of two counts, and converted to areas by using the map scale, and consequently areas of the occurances and hence the areas of each stratum were recorded as in Table 3.6.

Table 3.6 Estimated Strata Areas:-

Stratum	Area (ha)	Stratum	Area (ha)	Stratum	Area (ha)
1a	65.2	2e	20.7	4c	70.3
1b	107.0	2f	16.8	4d	69.3
1c	170.1	3a	6.1	4e	5.2
1d	387.5	3b	11.4	4f	9.7
1e	57.4	3c	39.5	5a	32.3
1f	184.2	3d	91.7	5b	105.5
2a	28.0	3e	9.2	5c	167.5
2b	8.2	3f	1.7	5d	151.8
2c	5.2	4a	5.0	5e	36.9
2d	137.3	4b	22.4	5f	15.6
	Total Area of Strata			=	2038.7 ha.

3.6 Sampling technique used:-

A double stratified random sampling design was used to estimate the standing timber volume for pine which consists of two phases as follows:-

Phase 1: Photo-interpretation:- a relatively large number of photo plots were located randomly in each selected stratum using the aerial photographs. For each of the selected eight strata, fifteen pilot photo plots were first selected randomly in randomly selected occurences by using co-ordinates from random number tables. This was done by placing a transparent paper grid (numbered on two adjoining sides) on the occurence on the photograph. The centres of the plot were pricked on the photograph at the selected random co-ordinates. After photo measurements (Section 3.72), a preliminary photo volume per ha for each plot was estimated (Section 4.21). The required total number of photo plots to achieve a desired precision of 10% of the mean volume per ha* was then calculated for each stratum by using formula No. (2) in Section 2.612.

Table 3.7 gives the summary of the calculated number of photo plots for the strata, based on the pilot sample of the plots.

Table 3.7 Calculated number of photo plots.

Stratum	First Estimation of n	2nd Estimation of n	Third Estimation of n	Final no. of photo plots.
1d	52	-	-	52
2d	53	-	-	53
3d	44	63	-	63
4d	42	49	-	49
5d	56	76	79	79
1f	47	-	-	47
~~1f~~ 1e	15	-	-	15
5e	29	43	54	54
Total				412

The distribution of the calculated number of photo plots for the different occurrences within a stratum was done by using probability proportional to size (P.P.S.) method, where the larger occurrences tend to receive more plots than the smaller ones. This was done by listing the occurrences of a stratum according to area in an ascending order so that the smallest occurrence appear at the top of the list while the largest appears at the bottom, Table 3.8 was

* at the 95% level of probability.

Table 3.8 The distribution of 52 photo plots in different occurences of stratum 1d using P.P.S. method:

Occurence No.	Area (ha)	Cumulative Area	No. of photo plots (from Random Tables)
22	1.00	1.0	
23	1.8	2.8	
18	1.8	4.6	
21	2.0	6.6	
15	2.5	9.1	1
13	2.5	11.6	
7	2.5	14.1	
1	2.8	16.9	
3	2.8	19.7	
12	2.8	22.5	
24	3.0	25.5	
5	3.0	28.5	1
11	3.2	31.7	
2	5.3	37.0	
19	6.9	43.9	2
17	8.8	57.7	4
16	10.2	62.9	1
10	11.5	74.4	1
9	16.9	91.3	3
20	17.1	108.4	3
4	20.6	129.0	4
14	39.7	168.7	4
6	71.0	239.7	8
8	147.8	387.5	20
			52

set as an example for Stratum 1d. Then in the next column cumulative areas were listed and random numbers between 1 and 388 were drawn from a random number table in order to distribute the 52 photo plots to the different occurences of Stratum 1d. The distribution of photo plots in occurences of all other strata followed the same method.

Phase 2: Field measurements:-

From previous experience a random sub-sample of 10 per cent of the photo plots were taken for field measurements (Howard.1970). The field plots were 44 in number at first, allocated to the eight selected strata according to their photo-volume variability. This was done by calculating the coefficient of variation (CV) for the strata and distributing the 44 plots in proportion to each stratum's CV, Table 3.9. Then for each stratum the calculated number of field plots were allocated to the different occurences by using the P.P.S. method described above.

Random number tables were used to select field plots in each occurence from the already existing photo plots on the photographs. The photo plots thus selected were marked as field plots on both the photographs and the map so that location in the field ~~will~~ would be easier.

As the result of actually measuring some of the plots in the field, some occurences of Stratum 5e in the western part of the survey area were corrected to stratum 5d after height measurements, and the same applied for stratum 1e, some of the occurences were corrected to 1f and others to 1d strata. Also some of the occurences of strata 5e and 1e were found to be exclusively of birch trees (measurements were done before proper species identification

Table 3.9 Allocation of Field plots to different strata:

STRATUM	No. of Photo-Plots.	Area of Stratum in ha.	Mean Vol/ha	Standard error %	Coefficient of Variation	No. of Field plots.
1f	47	084.20	315.46	6.82	0.23	4
1d	52	387.50	170.62	7.49	0.27	5
2d	53	137.30	153.92	7.72	0.28	5
3d	63	91.70	118.73	9.56	0.38	7
4d	49	69.30	90.11	9.72	0.34	6
5d	79	135.30	51.42	9.38	0.41	7
1e	15	157.40	239.31	9.55	0.17	3
5e	54	36.90	51.77	10.85	0.40	7
TOTAL	412	1099.60			2.48	44

in the area due to limited time), and thus these strata (5e and 1e) were very reduced in area due to this revision and consequently were disqualified as top strata and therefore were rejected ending up with six major strata having the most valuable amount of timber in the area, Table 3.10.

Table 3.10 Final selected top strata:

STRATUM	Area (ha)	No. of Photo Plots	No. of Ground Plots
1f	184.2	47	5
1d	387.5	52	5
2d	137.3	53	5
3d	91.7	63	7
4d	69.3	49	6
5d	151.8	79	7
TOTAL	1021.8	343	35

As the result of this, 35 field plots in total were selected and were actually measured, Section 3.8.

After completion of phase II, the photo parameters measured were ~~will~~ then ~~be~~ correlated to the timber volume measured on the ground to find out a suitable relationship, Section 4.23.

This double sampling design has proved to be flexible, efficient and economical under a wide range of conditions (Hutchinson 1978).

3.7 Selection of Strata and Measurements of Photo Plots:

3.71 Selection of Strata for measurement:-

Due to limited time for field work eight out of thirty strata were chosen at first for volume estimation on the basis of their possession of the most valuable amount of timber. The choice was started first by discarding all those strata having a total height of less than 13 m irrespective of their area and density since these strata do not possess a high-value merchantable timber. The remaining strata were then selected by considering area (Table 3.11).

TABLE: 3.11 Initial Selection of strata for volume estimation.

Stratum	Area (ha)	Per cent of area
1d	387.5	34.72
1e	157.4	14.10
5d	151.8	13.60
2d	137.3	12.30
3d	91.7	8.22
1f	84.2	7.54
4d	69.3	6.21
5e	36.9	3.31
TOTAL	1116.1	100

3.72 Measurements of photo plots:-

Measurements started after the completion of the random selection and marking of photo plots on the aerial photographs

(Section 3.6). The transparent measuring device (Figure 3.1) was then used to measure the plot area. Under the stereoscope, one circle was selected so that the centre of the photo plot exactly lay on the middle of the circle and was at the same time big enough to include at least ten trees. In the very sparse occurences, however, the largest circle on the overlay (with an area equivalent to 0.2916 ha) was used to accommodate only one or two trees in some cases, as larger circles may cause adjacent photo plots to overlap. Then the diameters of crowns of all the trees within the circle, or the photo plot, were measured under the stereoscope by the use of the micrometer wedge (Figure 3.2). This device has two converging lines scribed on a transparent material and the distance between the two lines is graduated. The wedge was placed so that the inside of each diverging line was just tangent to the outside dimension of the tree crown. If the crown was asymmetrical the maximum and the minimum diameters were measured and the mean was recorded, otherwise the diameter facing northeast and southwest directions was measured. The crowns of trees which were away from the centre of the photograph and therefore more radially displaced, were measured in such a way that the two diverging lines of the micrometer wedge were facing towards the centre of the photograph.

The main difficulty encountered was in very dense stands where separation of individual crowns was very difficult and also the counting of the trees. In most cases where crowns ~~are~~ were small and dense, only judgement was used to estimate the number of the crowns and consequently the measurement of the crown diameters proceeded.

FIGURE 3.1 : A measuring device for photo plot area, used as a film transparency.

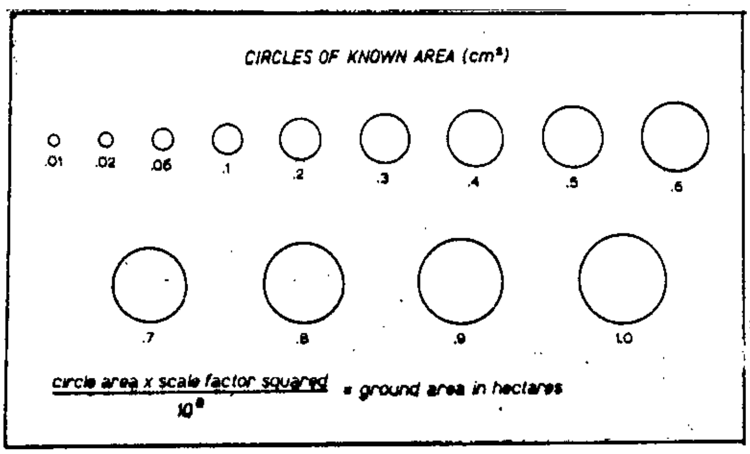
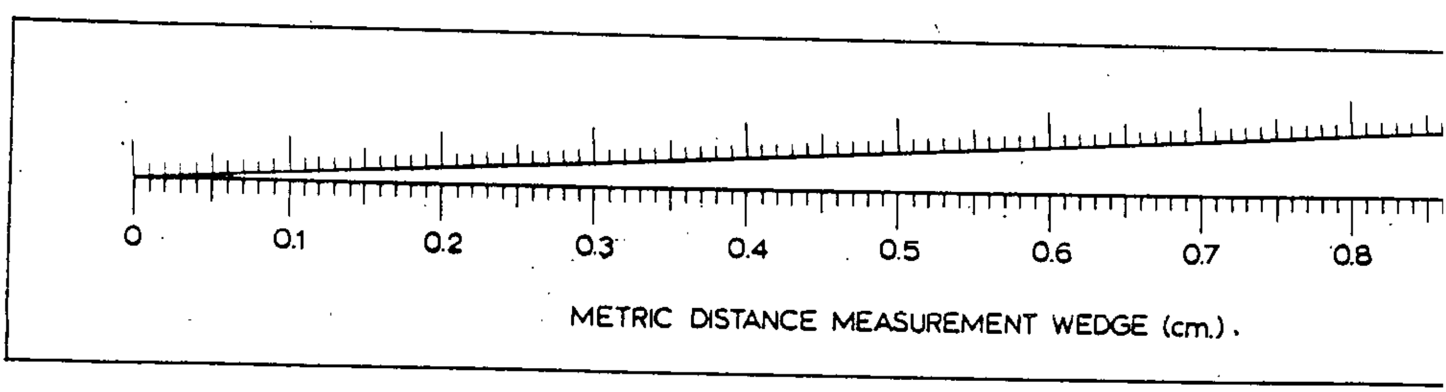


FIGURE 3.2 : The micrometer wedge.



These crown measurements were used to estimate the crown cover per cent in each plot (Photo Plots, Appendix A) by calculating the areas of the crowns and then expressed as a per cent of the plot area. This is considered more objective than crown closure measured by the method described in Section 2.553. These measurements will also be used to estimate photo volume as will be seen in Section 4.21.

As there are some areas of high ground especially at the southern and eastern periphery of the survey area where the scale of the photographs were not corrected due to time limit, the crown and height measurements were less accurate compared to the other major relatively flat area. This was corrected later after the field visit and correction of the scale. Appendix A shows the results of the measurements of crown diameters on some photo plots.

Height measurement, by the parallax method, was made on each plot for different measurable trees i.e. where both the top and base of the tree is visible, and the mean was recorded. The same procedure described in Section 3.4 was followed. Ten photo plots were measured, on the average, per day.

Due to limited time correction tables were not made in order to compare photo measurements near the nadir and those further away with ground measurements.

3.8 Measurements of Field Plots.

3.81 Plot Location in the Field:-

Both the map and the photograph were used for plot location in the field. Generally the map (Scale 1: 10,000) shows roughly where a plot is while the photograph (larger in scale 1: 5,000) shows its exact location, the centre of which being pricked by a pin. The photographs, being lighter and smaller than the map to carry round the field as well as showing more details, are more useful than the map for the purpose of plot location. On the photographs one can see, by the naked eye or by the help of a hand stereoscope, details like trees in different densities and heights, small gaps and clearings, raised grounds or valleys, buildings as well as trails and paths all of which cannot be recognised on the map.

Plots were located precisely in the field by using photographs as well as a compass. Before going into the forest the map was used to show the whereabouts of the plot and also to select the appropriate photograph. On arriving to the locality of the plot, obvious features such as road junctions, buildings, bridges, farm corners, large isolated trees etc., were selected and identified on both the ground and the photograph. Using these features a known distance on both the ground and the photograph was measured in order to find the exact scale of the photograph at that particular place. This was done because the photographic scale changes from place to place due to variation in elevation and also due to the change of the flying height for some reason or the other. Unfortunately scale correction cannot be made for all the field plots due to either the lack of distinctive features or due to the uneven ground around the plot which makes accurate measurement of distance on the ground very difficult. In these cases the nearest correction for scale was taken.

In general the central plain of the forest, which constitutes two thirds of the total survey area is represented by a scale of 1: 5400 in most places. The eastern part eastern of Longitude $3^{\circ}\ 44'$ W has a scale of 1 : 6,500 and the area west of Longitude $3^{\circ}\ 48'$ W has a scale of 1 : 7,400 on the photographs. This variation of scale on either side of the survey area is probably due to the presence of high mountains to the north and south of the eastern part and to the south of the western part and thus the flying height was increased in these regions to allow for the mountains heights.

After finding the correct photo scale around the field plot area, the nearest obvious feature to the plot was then selected and the correct direction from it to the plot centre was then found by photographic orientation and the use of a compass. From this spot the distance to the plot centre ~~is~~ was measured on the photograph and converted to met~~er~~res using the corrected scale. The distance to the plot centre was measured by pacing as it is difficult for one person to use the tape. The centre of the plot was further confirmed by identification of gaps or clumps or even individual trees on both the photograph and on the ground. In sparse occurences identification of trees or clumps g~~i~~ave a perfect clue for the location of the plot centre even without measuring distances. This last confirmation ~~is~~ was very necessary as it ~~is~~ was sometimes difficult to measure the exact distance to the centre of the plot on the ground because of the undulating ground level or because of changing direction due to some obstacle like ditches, fallen trees etc.

In dense stands it ~~is~~ was very difficult to identify individual trees on both the photograph and the ground, even if it happened that the plot centre was located by distance measurement with a 100 per cent accuracy. This is due to the continuation of the canopy which appear on the photograph as a merged coarse textured picture.

Four plots were found to be inaccessible (two of stratum 3d occurence 4, and two of stratum 2d occurrence number 4). It was not possible to locate their positions precisely because the first two were separated by a river and mountains, while the second two by a dense extensive forest merging into different other strata. It was difficult to locate the boundaries of the strata, in the field, as drawn on the photographs because the trees tended to merge gradually from one occurence to another and long distance measurements over undulating ground are not very reliable, especially when determined by pacing.

For the above reasons the four plots were replaced by more accessible ones through random choice. On the average two ground plots were located and measured per day.

3.82 Measurements in Field Plots:

Once the centre of the plot was located in the field, measurement of the plot radius was done from the centre by a tape so that the area will be the same as that of the photo plot. The following information was then collected from the established field plot (Appendix A):-

1. Total height (m) for all the trees in the plot
2. Timber height (m) " " " " " "
3. Diameter at breast height (DBH) (cm) for all trees.
4. Top diameter (cm) for all the trees.

5. Crown diameter (m) for all the trees.
6. Increment for two trees of the largest and smallest DBH (not less than 7 cm) in the plot.
7. Condition of the trunk for all the trees.

Number 1, 2 and 4 were measured by means of a Spiegel relascope. Top diameter was measured up to 7 cm and so was the timber height (rules in Section 4.3). Diameter at breast height (DBH) was measured by means of a tape, if the tree is forked at breast height or lower, it was considered as two trees and treated accordingly. Crown diameter was recorded as the mean of two measurements along the shorter and longer diameters of an obviously assymmetrical crown by pacing. It was the most tedious measurement in the field because no instruments were used and one has to look up and down several times, for every single tree, in order to be adjusted to the crown edges followed by horizontal distance measurement; specially when the sky is clear and bright, it causes some sort of strain in the eyes which lasts for a considerable amount of time.

Due to limited time only the largest and smallest DBH trees in the field plot were selected for increment measurements. Two borings (using an increment borer) were made for each tree at right angles at breast height; the width of the last five annual rings was measured by a ruler and the mean was recorded (Section 4.7 for calculations).

The general condition of the trunk was also recorded as whether it is in good form, forked, leaning, diseased or dead as well as whether the tree has a spreading crown or small crown.

CHAPTER FOUR

Analysis and Results.

Chapter 4.

Analysis and Results.

4.1 Relationship between diameter at breast height (DBH) and photo crown diameter (cd).

The purpose of determining this relationship was to estimate DBH from cd measured on the photograph and hence individual tree volumes (Section 4.21).

The individual trees examined for this relationship belonged to stands covering the full range of density and height. They were selected as trees which could be accurately identified both on the aerial photographs and on the ground. A total of 22 trees ~~were~~ was measured (Table 4.1); measurements of the crowns both on the photographs and on the ground followed the procedure described in Sections 3.72 and 3.82 respectively.

A regression of DBH, as the dependant variable, on cd produced the following equation:

$$DBH = 7.58\ cd - 6.69$$

where DBH is in centimet~~er~~res and cd in met~~er~~res.

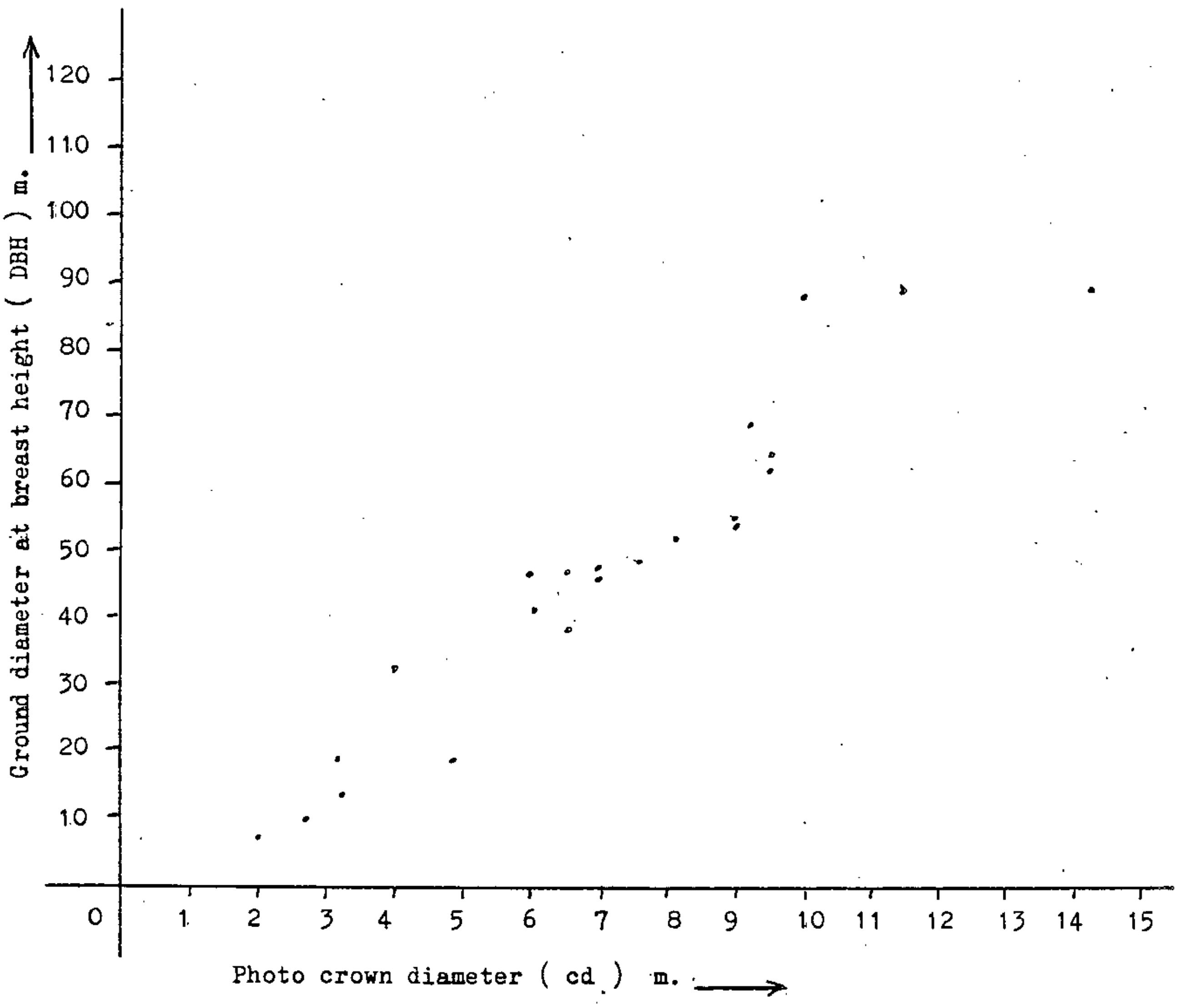
The data are also represented graphically as in Figure 4.1; the coefficient of determination (r^2) was found to be 0.90; r^2 for cd and CD is found to be 0.93. The photo crown diameter (cd) results (Table 4.1) are always less than the actual CD, and this confirms the fact that the thin branches at the periphery of the crowns are not resolved on the photographs.

Table 4.1.

Field and photo measurements of selected individual trees for DBH/cd relationship:

Tree No.	Field DBH cm	Field CD m	Photo cd m	ERROR cd-CD
1	47	7.4	6.5	-0.9
2	33	4.8	4.0	-0.8
3	55	9.6	9.0	-0.6
4	65	10.4	9.5	-0.9
5	88	11.7	10.0	-1.7
6	62	10.2	9.5	-0.7
7	41	6.2	6.0	-0.2
8	47	8.1	6.0	-2.1
9	69	10.3	9.2	-1.1
10	38	7.1	6.5	-0.6
11	52	8.2	8.1	-0.1
12	54	9.1	9.0	-0.1
13	49	8.4	7.6	-0.8
14	46	6.7	7.0	+0.3
15	48	7.6	7.0	-0.6
16	10	3.3	2.7	-0.6
17	19	3.8	3.2	-0.6
18	19	5.6	4.9	-0.7
19	13	3.7	3.2	-0.5
20	7	2.0	2.0	ZERO
21	88	15.0	14.2	-0.8
22	89	11.8	11.4	-0.4

FIGURE 4.1 : DBH/cd Relationship.



4.2 Volume Estimations.

4.21 Photo volume Estimation.

The volume per hectare in each photo plot (subsequently referred to as the "photo volume") was estimated by summing individual tree volumes. The median of the stratum height class was used to find an appropriate tariff number (Hamilton 1975, Table 11). The photo crown diameter (cd) was measured for each tree in the plot and DBH values were then estimated from the formula in Section 4.1. Tree volumes were taken from the appropriate Tariff Table (Hamilton 1975, Table 69) and the volume per hectare calculated (Appendix B). The estimation of mean photo volume and its variance and confidence limits for each stratum are described in Appendix C; Table 4.2 gives a summary.

Table 4.2: Summary of the calculations of standard error and confidence limits (C.L.) for estimated photo volumes.

Stratum	Mean photo Volume m^3 ha^{-1}	Standard error	C.L. as % of the mean.
1d	170.60	6.4	7.5
2d	153.9	5.9	7.7
3d	118.7	5.7	9.6
4d	90.1	4.4	8.8
5d	52.2	4.9	9.4
1f	315.5	10.8	6.8

4.22 Volume Calculations in field plots:

The height growth of very dense trees, in natural or semi-natural forests, is increased at the expense of diameter due to competition for sunlight and this gives rise to long narrow crowns and good stem form. In contrast, however, less dense and scattered trees tend to have bigger crowns and branches with shorter often forked or with multiple stems as the result of forking above a height of one to two meters, (Plate 1).

Between these two extremes trees of different densities show a number of crown shapes and stem form in different localities.

There is no one reliable method which can be followed to measure timber volume for these various kinds of trees in the field, other than felling them for direct measurement which could not be done in the survey area; consequently, the following rules were set in order to measure timber volume for the trees in the field plots as objectively as possible:-

(i) Only the utilisable timber of the tree is measured.

(ii) The timber height is measured up to 7 cm top diameter (over bark) provided that the tree is straight.

(iii) If the tree has a fork with an angle more than 45°, the total timber height is taken below the fork, unless one limb continues in the same vertical plane as the main stem.

(iv) If the tree has a fork with an angle less than 45°, and both limbs continue in the vertical plane, the largest will be considered as the main stem. If both branches are of the same size, both will be taken in consideration.

According to the above rules large branches, with diameters more than 7 cm, not in the vertical plane will not be measured.

For volume calculations for every tree in the field plot, Smalian formula was used:

$$V = \frac{(S_1 + S_2)}{2} \cdot \ell$$

where V = volume of the tree in m^3

S_1 = basal cross-sectional area in m^2.

S_2 = top cross-sectional area in m^2.

ℓ = timber height in metres.

The diameter at breast height (DBH) was taken as the basal diameter. Data collected for the volume calculation per hectare in each field plot (subsequently referred to as "ground volume") are shown in Appendix A, and a summary of the calculations for all the field plots are given in Appendix D.

4.23 Volume estimation from aerial photographs.

4.231 Volume estimation:

Using the data in Appendix D, linear regression analysis was carried out using the University computer, PRESTO system established by the members of staff, in order to find out the best photo parameter(s) as independant variable(s) to predict ground volume.

As stratum 1f differed in height from the rest of the five d-type strata, it was found convenient to carry out the correlations and analysis with the d-type strata combined. Moreover, since there are only five ground plots in stratum 1f it was not possible to carry out a separate regression analysis for this stratum which was subsequently ignored.

For the rest of the strata ten models were tried on the basis of correlation coefficients. The correlation coefficients between photo parameters and ground volume of the d-type strata are summarised as follows:-

Correlation Matrix

	PVOL	PHT	PCC	GVOL
PVOL	1.0000	-	-	-
PHT	0.3573	1.0000	-	-
PCC	0.9935	0.3471	1.0000	-
GVOL	0.8521	0.4734	0.8770	1.0000

The models tried are:-

1. $GVOL = a + b_1 \cdot PCC$
2. $GVOL = a + b_1 \cdot PVOL$
3. $GVOL = a + b_1 \cdot PVOL + b_2 \cdot PCC$
4. $GVOL = a + b_1 \cdot PVOL + b_2 \cdot PHT$
5. $GVOL = a + b_1 \cdot PCC + b_2 \cdot PHT$
6. $GVOL = a + b_1 \cdot PCC + b_2 \cdot PHT + b_3 \cdot PVOL$
7. $GVOL = a + b_1 \cdot P_1VOL$
8. $GVOL = a + b_1 \cdot P_1VOL + b_2 \cdot PCC$
9. $GVOL = a + b_1 \cdot PHT + b_2 \cdot P_1VOL$
10. $GVOL = a + b_1 \cdot P_1VOL + b_2\ PCC + b_3 \cdot PHT$

where GVOL = Ground Volume ($m^3\ ha^{-1}$)

*PHT = mean stand photo height (m)

*PCC = photo crown cover per cent.

*PVOL = photo volume ($m^3\ ha^{-1}$)

*P_1VOL = photo volume ($m^3\ ha^{-1}$)

re-estimated using the plot photo height rather than mean stratum height (Appendix D).

*All measured in photo plots corresponding to ground plots.

The model to be selected is the one which best satisfied the following criteria: have the highest coefficient of determination (r^2), smallest standard errors of regression coefficient(s), a higher F-value at P0.05 and practicality of the independent variable(s).

The results of the regression analysis are summarised in Table 4.3. The correlation results showed that there ~~is~~ was no reason to suspect a curvilinear relationship and therefore no attempt was made to fit curves to the data.

Model number 1 was selected as having a high r^2, low standard errors of coefficients, a higher F-value as well as being more practical due to the simplicity and precision of photo crown cover measurements. Accordingly the following formula was used to calculate GVOL for the rest of the photo plots in the d-type strata (Appendix E):-

GVOL = 2.85 PCC + 2.59

Values of PCC for all photo plots were calculated by using the crown diameters of the trees measured in the plots together with the plot area (Appendix D). A graph of GVOL VS PCC was constructed (Figure 4.2) to show the linear relationship between the two.

4.232 Crown cover estimation.

Crown cover per cent was calculated as described in Section 3.72. A comparison between field and photographic measurements of crown cover was made (Table 4.4, Figure 4.3).

The above mentioned computer and system was then used for

TABLE 4.3 Results of the Regression Analysis for the different models.

Model	a Value	b_1 Value	b_2 Value	b_3 Value	Coefficient of multiple determination (r^2)	Standard errors of partial regression coefficients a	b_1	b_2	b_3	F-Value at P0.05
1	2.5877	2.8504	-	-	0.7692	11.79	0.29	-	-	93.30*
2	1.1694	0.9052	-	-	0.7261	13.28	0.11	-	-	74.23*
3	11.0300	-1.5699	7.6221	-	0.7975	12.06	0.81	2.47	-	53.18*
4	-74.7300	0.8317	6.0300	-	0.7588	41.64	0.16	3.15	-	42.48*
5	-73.2800	2.6300	5.9800	-	0.8016	37.77	0.30	2.85	-	54.56*
6	-73.0900	8.0500	6.7300	-1.7900	0.8380	34.78	2.26	2.64	0.74	44.84*
7	5.6750	0.8574	-	-	0.7552	11.94	0.09	-	-	86.40*
8	2.5836	0.2590	2.0162	-	0.7722	11.93	0.43	1.42	-	45.76*
9	-26.2000	0.8187	2.5981	-	0.7607	42.50	0.11	3.32	-	42.90*
10	-105.3000	0.5390	4.2780	0.5110	0.8090	49.47	0.54	1.67	3.80	36.71*

*Significant at P0.001.

Figure 4.2 : Ground volume versus Photo crown cover.

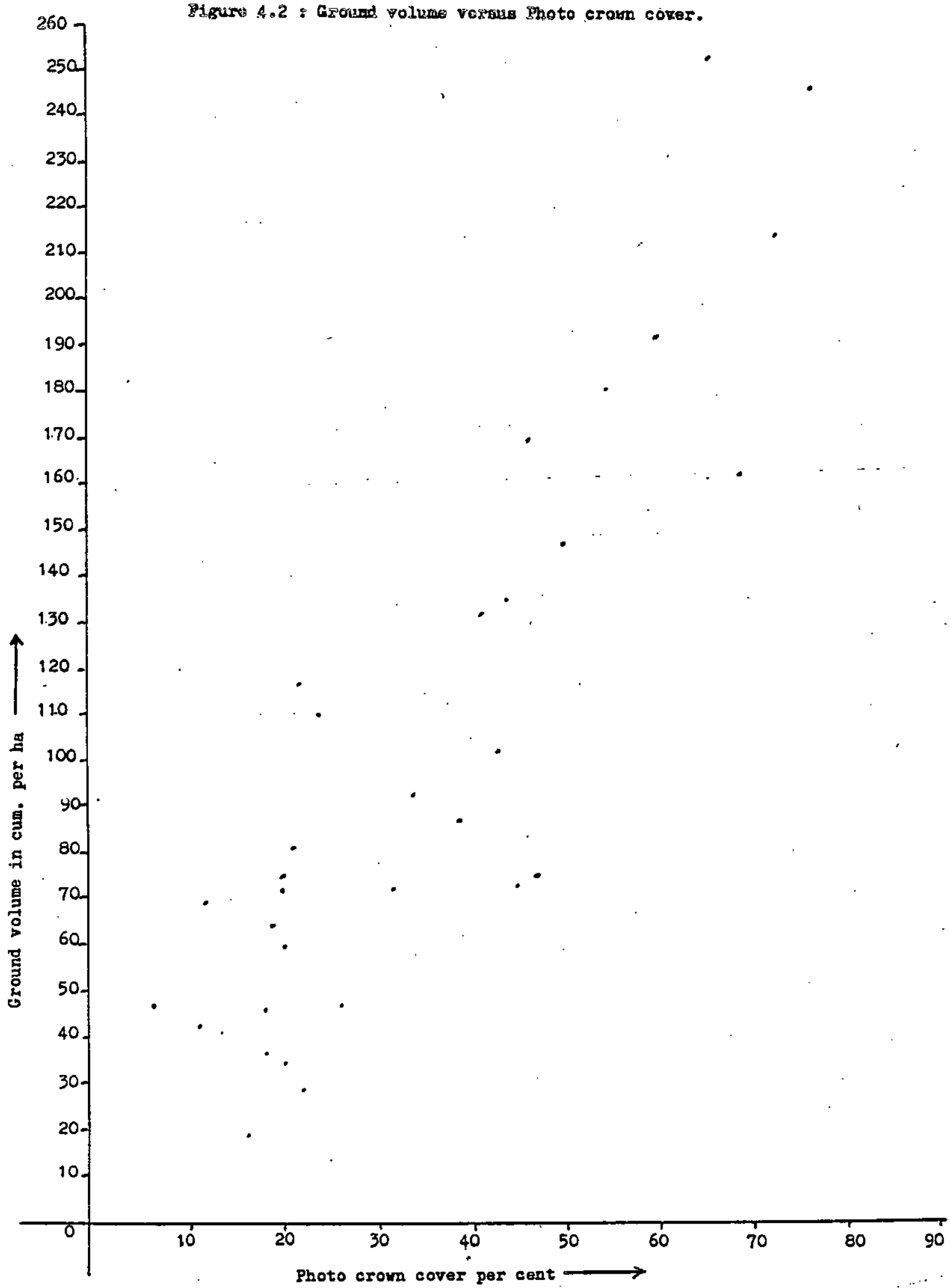
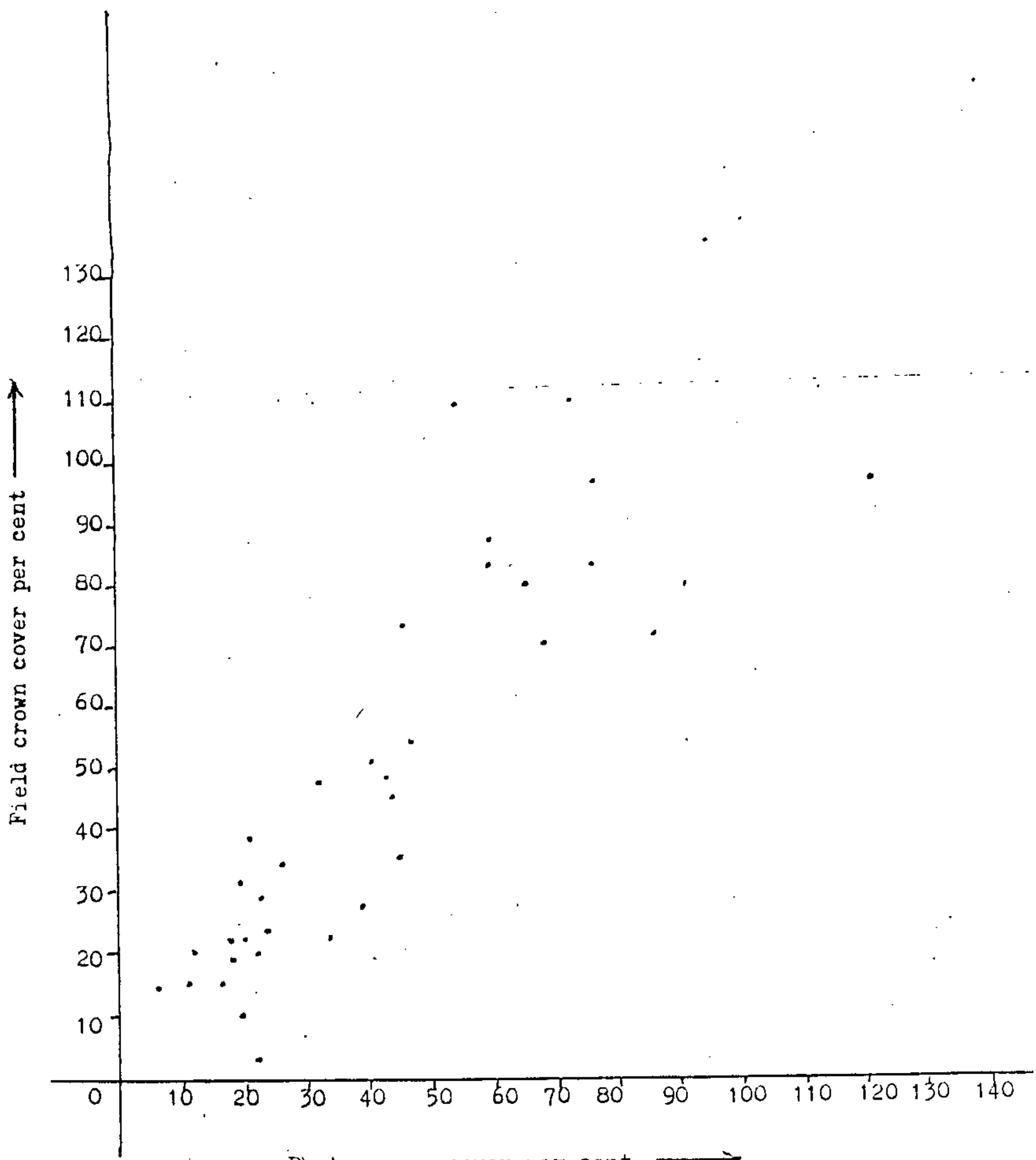


TABLE 4.4 Comparison of Field Measurements with photographic measurements of crown cover.

STRATUM	Plot No.	Crown cover per cent FIELD (GCC)	PHOTO (PCC)	Error PCC-GCC	As percentage of PCC
1d	9	73	46	-27	-59
	10	83	77	- 6	- 8
	11	80	66	-14	-21
	2	109	73	-36	-49
	3	70	69	- 1	- 1
2d	1	86	60	-26	-43
	1	54	47	- 7	-15
	1	29	22	- 7	-32
	2	45	44	- 1	- 2
	2	109	55	-54	-98
3d	6	31	20	-11	-55
	4	23	24	+ 1	+ 4
	1	47	32	-15	-47
	6	27	39	+12	+31
	13	48	43	- 5	-12
	1	38	21	-17	-81
	1	51	41	-10	-24
4d	8	10	20	+10	+50
	2	22	20	- 2	-10
	1	15	16	+ 1	+ 6
	5	35	45	+10	+22
	1	34	26	- 8	-31
	1	22	18	- 4	-22
5d	8	22	34	+12	+35
	1	19	18	- 1	- 6
	1	20	22	+ 2	+ 9
	1	19	19	zero	zero
	7	15	11	- 4	-36
	5	20	12	- 8	-67
	1	14	6	- 8	-133
1f	1	83	60	-23	-38
	4	96	77	-19	-25
	12	96	122	+26	+21
	7	134	96	-38	-40
	7	71	86	+15	+17

FIGURE 4.3 : Field crown cover versus Photo crown cover.



regression analysis on the data; the following models were tried:-

1. $GCC = a + b. PCC$

2. $GCC = a + b. \sqrt{PCC}$

3. $GCC = a + b. PCC^2$

4. $\log GCC = \log a + b. \log PCC \quad (GCC = a \cdot PCC^b)$

where GCC = ground crown cover; PCC = photo crown cover per cent.

The results are summarised in Table 4.5.

TABLE 4.5 Summary Results of Crown Cover Models:

MODEL	a value	b value	r^2	Standard errors of partial regression coefficients a	b	F-Value P0.05
1	4.4913	1.0712	0.7756	5.0562	0.1003	114.09*
2	-38.9870	14.3743	0.7887	8.4432	1.2953	123.14*
3	28.7186	0.0084	0.6263	4.5311	0.0011	55.32*
4	0.1808	0.9232	0.8060	0.1243	0.0789	137.08*

*Significant at P0.001.

Model 4 was found to be the best suited since it satisfies the above-mentioned criteria. It is calculated as follows:

$$\text{Log } GCC = 0.1808 + 0.9232 \log PCC.$$

In some cases as in Table 4.4, the photo crown cover is greater than the ground crown cover measurement in some plots, this was due to shadows and dark spots which were misinterpreted as crowns. In other plots ground measurements of crown cover are much greater than the photo measurements, usually in dense plots, and this is attributed to overlapping crowns of the dominants and subdominant trees as well as to the smaller trees which cannot be seen on the photographs.

4.24 Accuracy of the estimated Volume.

Table 4.6 summarises the standing volume for the five main strata (Calculations are shown in Appendix F). The estimated volume (Section 4.23) is within the set accuracy i.e. within a confidence limit of 10 per cent of the mean.* When this table is compared with Table 4.2, it can be concluded that the accuracy of the final volume estimate is similar to that of the preliminary photo volume estimate.

There are two measurable components of variance, in double sampling the variance about the regression line and the variance among field-measured plots. The following equation (Paine 1981) is used to obtain the standard error of the mean for the adopted double sampling with regression:-

$$SE_{\bar{y}} = \sqrt{S^2_{y.x} \left(\frac{1}{n_2} + \frac{(\bar{x}_1 - \bar{x}_2)^2}{SS_x} \right) \left(1 - \frac{n2}{n1}\right) + \frac{S^2_y}{n_1} . \left(1 - \frac{n1}{N}\right)}$$

where $SE_{\bar{y}}$ = Standard error of the mean for double sampling with regression.

$S^2_{y.x}$ = variance about the regression line

$$= \frac{SS_y - \frac{(SP_{xy})2}{SS_x}}{n_2 - 2} = 1181.11$$

Sy^2 = variance of the field volumes

= $SSy/n_2 - 1 = 4179.10$.

SS_x = net sum of squares (SS) of photo plots that were also selected for field measurement = 107393.53

$\bar{x}_1$ = mean of all unadjusted photo volumes = 111.13 m^3ha^{-1}

$\bar{x}_2$ = mean of the unadjusted photo volumes that were also

* at the 95% level of probability.

<u>Table 4.6</u> Summary of Stand parameters for the five main strata.

STRATUM	Area (ha)	Basal Area $m^2\ ha^{-1}$	Mean PCC	No of trees per ha	Mean Stand Volume $(m^3\ ha^{-1})$	Standard error of the mean	C.L. as per cent of the mean	Total Volume of Stratum (m^3)	C.L. of total volume (m^3)
1d	387.5	52.9	66	335	162.5	6.36	7.8	62968.8	4912
2d	137.3	33.8	46	161	138.1	5.37	7.8	18961.1	1479
3d	91.7	18.3	31	54	104.7	5.05	9.6	9101.0	922
4d	69.3	9.9	24	48	80.9	3.75	9.3	5606.4	521
5d	151.8	10.8	17	33	45.7	1.88	8.2	6937.3	569
TOTAL	837.6							104074.6	8403

measured in the field = 111.37 m^3 ha^{-1}

n_1 = number of photo measured plots = 296

n_2 = number of field measured plots = 30

N = total possible number of plots in the population

if sampling without replacement = 4291

SS_y = SS of field plots = 121193.99

$$SP_{xy} = \Sigma xy - \frac{(\Sigma x)\ (\Sigma y)}{n} = 97282.15$$

(x and y being photo and field volumes respectively).

$$\therefore SE_{\bar{y}} = \sqrt{35.38 + 13.14} = 6.97$$

The ~~adjusted~~ mean of all the plots (296) is found to be <u>101.16</u> m^3 ha^{-1}

The standard error as a per cent of the mean = $\frac{6.97}{101.16}$ x 100 = <u>6.9%</u>

The total volume for the d-type strata = Total area X ~~adjusted~~ mean ~~mean~~ = 837.6 x 101.16 = <u>84731.6</u> m^3

From Table 4.6 Total volume was found to be 104074.6 a difference of 19343.0 m^3 which is equivalent to about 19 per cent of the estimated volume.

4.3 Height measurements.

Photo height was measured in order to calculate plot photo volume (Section 4.23) and secondly to compare with Lorey's mean height, calculated from field plot data, in order to test the accuracy of photostratification (Table 4.7).

Lorey's mean height (h_L) was calculated by using the following formula:-

$$h_L = \frac{\Sigma h_i g_i}{\Sigma g_i} = \frac{\Sigma h_i d_i^2}{\Sigma d_i^2}$$

TABLE 4.7 Photo heights and Lorey's mean heights for the field plots.

Stratum	Plot No.	Photo height (m)	Lorey's mean ht. (m)	Error
1d	9	13.01	13.54	-0.53
"	10	15.99	14.62	+1.37
"	11	15.27	15.37	-0.10
"	2	15.41	15.15	+0.26
"	3	16.18	18.33	-2.15
2d	1	12.71	13.23	-0.52
"	1	12.19	10.87	+1.32
"	1	16.41	18.06	-1.65
"	2	14.51	15.71	-1.20
"	2	14.93	13.44	+1.49
3d	6	14.67	14.79	-0.12
"	4	19.11	19.59	-0.48
"	1	14.88	14.60	+0.28
"	6	15.18	16.90	-1.72
"	13	14.08	14.24	-0.16
"	1	10.96	12.69	-1.73
"	1	15.43	16.95	-1.52
4d	8	14.14	14.86	-0.72
"	2	15.02	16.88	-1.86
"	1	10.12	10.35	-0.23
"	5	12.29	13.16	-0.87
"	1	13.95	11.86	+2.09
"	1	11.67	11.54	+0.13
5d	8	15.05	15.20	-0.15
"	1	12.95	12.95	ZERO
"	1	9.72	10.49	-0.77
"	1	13.77	12.23	+1.54
"	7	15.48	16.75	-1.27
"	5	12.09	13.87	-1.78
"	1	11.01	13.99	-2.98
1f	1	19.18	20.85	-1.67
"	4	15.94	17.32	-1.38
"	12	21.10	18.28	+2.83
"	7	20.98	19.04	+1.94
"	7	21.55	18.91	+2.64

where h_i = height of ith tree

g_i = basal area of ith tree

d_i = diameter at breast height of the ith tree.

Results of the comparison of the mean heights for the strata are made by the calculation of t - values, Table 4.8; Appendix G shows the method of calculation of t for comparison of two means.

As the tabulated t - value for each stratum at P0.01 is far greater than the calculated t - value, it is concluded that there is no significant difference between the two means and hence photo measurement for height stratification is very reliable.

The actual mean height (Lorey's)

Table 4.8 Strata height means and calculated - t values:

STRATUM	Stratum height range (m)	Mean Photo height (m)	Mean Loreys height for Stratum (m)	Calculated t - value.
1f	19-21	19.75	18.88	0.73
1d	13-15	15.17	15.40	0.24
2d	13-15	14.15	14.26	0.08
3d	13-15	14.90	15.68	0.62
4d	13-15	12.87	13.11	0.19
5d	13-15	12.87	13.64	0.70

falls exactly within the stratum height range (Table 4.8) and so the mean photo height.

4.4 Branchiness.

Foresters are mainly interested in growing trees of good form which makes utilization and harvesting easier and more efficient. Branched trees, on the other hand, which were usually eliminated during thinnings, occupy a lot of space and may deform neighbouring trees and compete strongly for sunlight and essential nutritive elements. Their characteristic feature is a short thick bole and large spreading branches, Plate I. Plenty of time is wasted in the felling and conversion of a branchy tree which increases the cost of harvesting. Furthermore, the unit value of such timber is lower than that of a well-formed tree.

Such kinds of branched trees occur mainly in open natural or semi-natural forests. Table 4.9 shows the higher percentages of branched trees occuring in more open stands than in dense ones in the survey area.

It is often very difficult to measure and estimate the volume of branched trees in a field plot as the main stem divides into many diverging branches of various sizes. Figure 4.4 shows the comparison between volumes of good form trees and branched ones (data in Appendix H). It is clear that branched trees have less estimated volume than good formed trees of the same diameter at breast height (DBH). It can also be noticed that trees of good form with DBH more than 60 cm rarely exist in the survey area, which is indicative ~~to~~ of selective fellings, and nearly all trees with DBH larger than 60 cm are branched trees.

4.5 Estimation of Periodic mean Annual Basal Area Increment:

Increment cores were taken at breast height with a Pressler's borer from the largest and smallest trees (DBH exceeding 7 cm) in each ground plot. The radial increment over the last 5 years

TABLE 4.9 Percentages of branched trees:

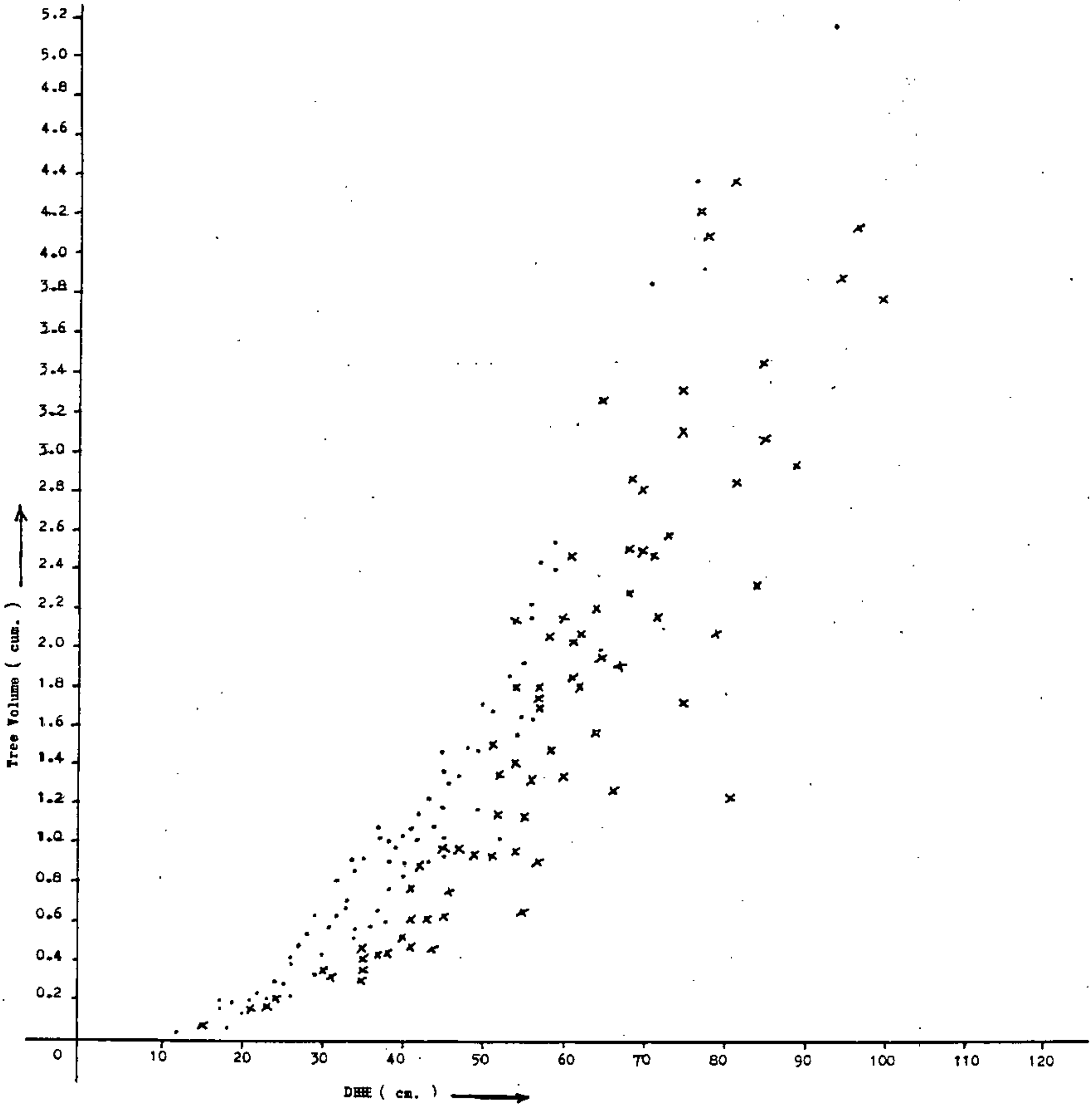
Stratum	Number of Branched trees	Number of good form trees	Total number of trees	% age of Branched trees
1d	5	62	67	7.5
2d	28	31	59	47.5
3d	46	19	65	70.8
4d	27	18	45	60.0
5d	40	16	56	71.5

PLATE 1 The characteristic feature of a branched tree showing the short bole and large spreading branches.

FIGURE 4.4 : Volume of good form and branched trees against Diameter at breast height (DBH).

• Good form Trees.

x Branched Trees.



was recorded as the mean of two measurements (Appendix I). The periodic mean annual basal area increment was, calculated (Appendix J) using Pressler's formula as follows:-

$$PMAI\% = \frac{g_o - g_n}{g_o + g_n} \times \frac{200}{n}$$

where PMAI% = periodic mean annual basal area increment (per cent).

g_o = present basal area

g_n = basal area n years ago

n = period (five years).

A graph of basal area increment per cent was plotted against mean tree size (Figure 4.5). Being ~~a~~ curvilinear, the following models were tried (using the computer) in order to find a suitable relationship between increment and tree size:-

1. $Y = a + b_1 x + b_2 x^2$
2. $Y = a + b_1 x + b_2 x^2 + b_3 x^3$
3. $Y = a + b_1 \log x$
4. $\log Y = \log a + b_1 \log x \quad Y = a x^b$

where Y = periodic mean annual basal area increment per cent.

x = mean tree size (DBH (cm))

a, b_1, b_2, b_3 = constants

The results of calculation are shown in Table 4.10.

FIGURE 4.5 : Basal Area Increment per cent against Mean DBH.

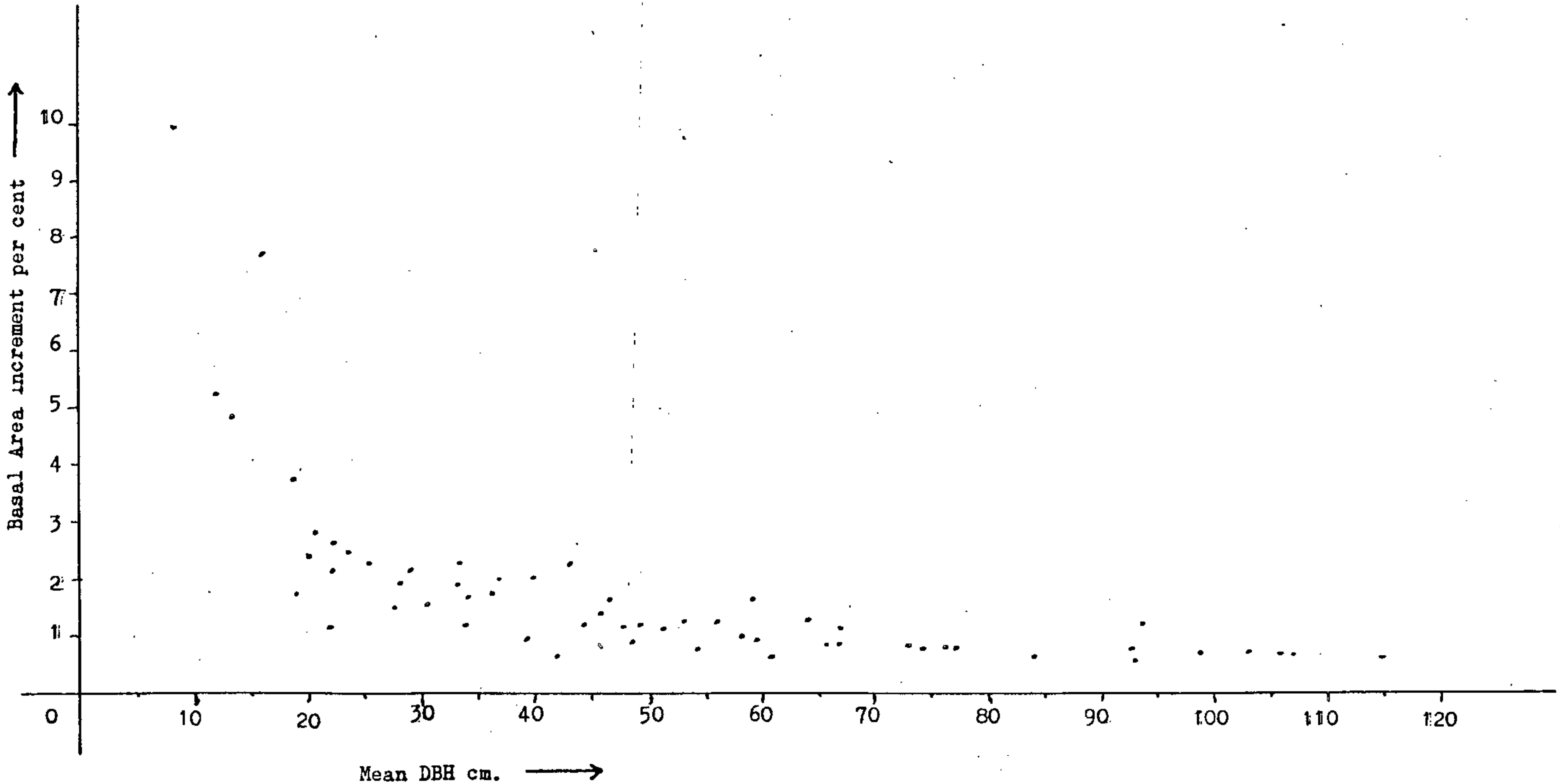


Table 4.10 Results of the regression analysis for increment models.

MODEL	a value	b_1 value	b_2 value	b_3 value	r^2	Standard error of partial regression coefficients a	b_1	b_2	b_3	F-Value P0.05
1	6.15	-0.15	0.001	-	0.59	0.54	0.02	0.0002	-	42*
2	9.53	-0.90	0.006	0.00	0.72	0.81	0.05	0.0010	0.00	48*
3	9.88	-4.95	-	-	0.60	0.89	0.53	-	-	86*
4	1.39	-0.61	-	-	0.76	0.07	0.04	-	-	184*

*Significant at P0.001.

Model number 4 was found to be the most suitable on the basis of the criteria mentioned in Section 4.23. Model 4 therefore becomes as follows:-

$$\log Y = 1.39 - 0.61 \log x$$

Because trees of different sizes grow at different rates, a weighted average periodic annual increment was calculated for each stratum (Table 4.11). The test of significance between weighted means was made between the highest and lowest values by calculating t (Appendix G). The test shows no significant difference between these two means and hence it can be concluded that there is no significant difference between all the weighted means. This implies that all strata have similar rates of ~~diameter~~ basal area growth. But usually open grown trees grow faster than closed ones due to minimum competition and consequently it can be said that strata 3d, 4d and 5d are growing slower than 1f, 1d and 2d. This slow rate of growth may be attributed to site factors as most of the former strata are growing on more exposed sites and on soils with poor vertical drainage.

Table 4.11 Comparison of weighted means of the basal area increment.

STRATUM	Basal Area (m^2 ha^{-1})	Basal Area Increment per cent Arithmatic mean	Weighted mean	t-value for * highest and lowest basal area weighted mean increment %.
1f	46.3	1.20	0.91	0.54*
1d	52.9	2.12	1.06	
2d	33.8	2.10	0.91	
3d	18.3	1.47	1.00	
4d	9.9	1.44	0.98	
5d	10.8	1.77	0.93	

Mean of weighted means $= \dfrac{\Sigma(\Sigma i.g)}{\Sigma(\Sigma g)} = \underline{\underline{0.97}}$

where i = PMAI

g = basal area

* Appendix G for calculation of t.

CHAPTER FIVE

DISCUSSION AND CONCLUSIONS

CHAPTER FIVE

Discussion and Conclusions

5.1 Discussion

5.11 Stand volume estimation:

The good correlation of photo crown diameter (cd) and diameter at breast height measured on the ground (DBH), $r^2 = 0.9$ Section 4.1, permitted the estimation of photo tree volumes, photo plot volume per hectare and consequently the ~~calculation~~ estimation of the number of photo sample plots required. The fact that thin branches at the periphery of crowns are not resolved on the photographs does not affect this relationship significantly (compared to the DBH/ground crown diameter (CD) relationship).

In Rothiemurchus Forest, timber volume in five combined strata of different densities but of the same height class (13 - 15 m) was found to be strongly correlated with crown cover per cent measured on aerial photographs (PCC). This correlation was expected because leaf area is known to be well correlated with stem volume production. A comparison of an objective measurement of PCC (Sections 3.72; 4.232) and an occular estimation on the photographs (Section 2.553) showed the latter to be adequate for both stratification and the estimation of timber volume.

Ten models were tried in order to find out the best correlation between ground volume (GVOL) as the dependent variable and photo variables (Section 4.231). It was found that the inclusion of more photo variables in addition to canopy closure would slightly improve the coefficient of determination (Table 4.3), but it is important that the model should be as simple and practical as possible so that the use of highly specialised personnel and/or equipment may be avoided. Thus the first model (GVOL VS. PCC) was selected for timber volume estimation in the five strata. Ground volume can thus be directly obtained from photo crown cover per cent (PCC) which saves a lot of time compared to the method of measuring crown diameters of individual trees and then estimating ground volume per hectare as the sum of individual tree volumes.

The double stratified random sampling gave results of adequate precision from relatively few field plots (Section 2.24), thus saving a large amount of field work. Due to limited time not all the strata were measured and even for those measured there were not enough data to construct a regression line for each stratum.

This approach will be very appropriate in natural or semi-natural forests in general and in Rothiemercus Forest in particular because many strata have numerous scattered occurrences and direct ground measurement for separate regression analysis would be expensive and time consuming.

The results of mean volumes per hectare for both ground and photographic estimation from the regression equation (Table 4.6 and Appendix D) show that the regression was least accurate for very dense stands and for the sparse stands of stratum 4d in particular. In the former case the crowns of the dominant trees appear on the photographs while the codominants and the supressed trees are hidden beneath the dominants, this means crown cover is measured only for the dominant trees appear on the photographs while the codominants and the supressed trees are hidden beneath the dominants, this means crown cover is measured only for the dominant trees and hence volume estimation from the regression accounts for dominant trees only in very dense stands. In the latter case it was noticed in the field that most of stratum 4d is in a poor waterlogged site and the trees have spreading crowns with small boles and hence a smaller volume of timber for a given crown diameter.

In sparse stands future studies should investigate the correlation of volume of coarsely branched trees with photo parameters, e.g. crown diameter and/or height, as well as the distinction between large trees and clumps for more accurate volume estimation.

It is evident from the calculations of the standard error of the mean volume (Section 4.24), that about two thirds of the variance is contributed by the regression and the rest by field measurements. Therefore more plots should be measured in the field to reduce the former.

The above calculations cannot be done for the individual strata due to the small number of ground plots which would result in unrealistically large variances.

For further investigations it would be desirable to compare crown diameter measurements near the nadir (of a photograph) and those further away, as the measurements of the latter are usually overestimated due to radial displacement. This was not carried out due to limited time.

In addition the correction of photographic scale in the steeply sloping areas should be carried out more precisely.

Large percentages of branched trees were found to occur mainly in less dense stands (Section 4.4), but no attempt was made to identify branched trees on aerial photographs. Due to branchiness a great deal of utilizable timber is not accurately estimated (Figure 4.4). Therefore, more information is necessary to provide precise estimates of volumes of firewood and timber in branched trees.

5.12 Increment:

Limited investigation of basal area increment per cent (BAI %) was made by measuring only two trees (the largest and smallest, DBH not less than 7 cm) per ground plot in order to cover the size (or DBH) range. It is considered desirable to have some information of increment for mature trees, where height increment has slowed down or stopped and thus basal area increment will be equivalent to volume increment.

Although the BAI% decreases with age (in addition to annual climatic variation), comparison between strata is meaningful because the d-type strata have the same height class and therefore approximate same age class.

Results show similar rate of growth (Table 4.11) for all the measured strata which suggests that poorly stocked strata are on poor sites since open grown trees might be expected to have higher rates of BAI%. The possible reasons for poorer sites are exposure and poor vertical drainage.

5.13 Stratification.

Thirty strata of Scots pine (Section 3.4; Table 3.5) as well as birch stands and non-forest areas were identified and delineated on the aerial photographs. The pine stratification was done on the basis of photo height and crown cover per cent. Comparisons of the mean photo height with Lorey's mean height (Section 4.3) showed no significant difference between them, and so photo height and occular estimation of crown cover per cent (Section 5.1) proved to be reliable parameters for stratification. In addition the differences between mean volumes for the d-type strata (Table 4.6) as well as the degree of variation within strata (confidence limits of less than 10%) confirms the precision of the stratification. The errors of volume tables and other mensurational data do not affect the stratification itself since it does not take into consideration assumptions like merchantibility, tree form etc.

As the result of stratification more accurate volume estimation for the five strata was obtained. The estimated total volume for the whole area without stratification was 19% less than the sum of individual stratum volumes (Section 4.24).

Stratification is useful in establishing a sampling frame from which sampling units can be drawn objectively. It is also useful for intensive management of the woodlands, e.g.- the allocation of areas for different activities and the prescription of different methods of exploitation. Areas for timber sale, for example, can be selected and topographic features that influence cutting boundaries, logging methods, soil stability and road layout can be studied more intensely on the aerial photographs.

The same basic stratification could also be used to estimate the volume of other types of produce, for example, branchwood for pulp or fuel.

5.2 Conclusions:

1. The use of aerial photographs in forest inventory proved to save a great deal of field work in order to obtain standing volume estimates of the required accuracy.

2. Stratification on aerial photographs can be done with adequate precision for the purpose of volume estimation in a semi-natural forest. In the study area, it improved volume estimation by about 19%.

3. The two-phase stratified random sampling design (or double sampling) produced results of good precision from relatively few ground plots. Thus it can be applied with confidence in similar situations of natural or semi-natural forests.

4. Good correlations exist between the following field and photo parameters in Rothiemurchus Forest:-

a. Diameter at breast height (DBH) and photo crown diameter (cd).

b. Ground volume (m^3 ha^{-1}) and photo crown cover per cent (PCC).

c. Ground crown cover (GCC) and photo crown cover (PCC).

d. Lorey's mean height and photo mean height for sample plots.

e. Ground and photo number of trees per hectare especially in less dense strata.

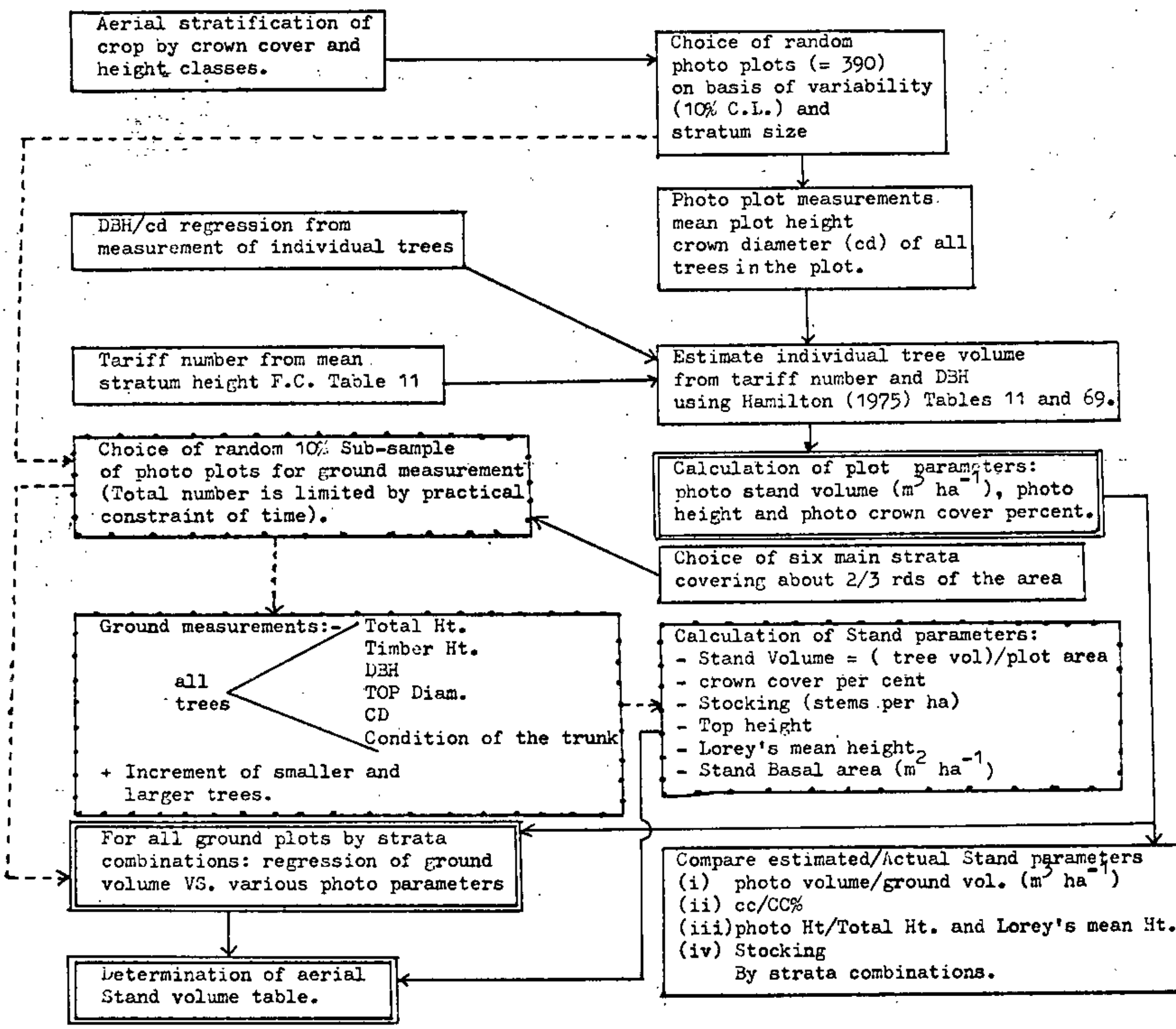
5. The component of variance in ground volume derived from the regression on photo crown cover was found to be greater (2/3 rds of total) than that of the field plot measurements.

6. The estimated volume of branched trees is lower than those of good form of the same size (DBH).

7. The six main strata were found to have similar rates of diameter growth and hence basal area increment for equivalent size classes. This indicates that more open stands are found on poorer sites, mainly due to exposure or poor vertical drainage.

8. Flow diagram (next page).

8 - Flow diagram to show the steps carried out to achieve the results of the inventory:-



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APPENDIX A.

Data collected from Field and Photo plots. One field plot and the corresponding photo plot are selected for each stratum.*

* The Rest of the field and photo data can be seen in the Dept. of Forestry and Natural Resources, University of Edinburgh.

FIELD PLOT.

STRATUM 1d OCCURRENCE 8 PLOT NO. 9 PLOT AREA 0.0583 ha.

TREE NO.	HEIGHT (m)		DIAMETER (cm)		CROWN DIAMETER (m)	INCREMENT FOR LAST FIVE YEARS (cm.)	CONDITION OF TRUNK AND CROWN
	TOTAL	TIMBER	DBH	TOP			
1	12.5	10.5	37	15	6.0	-	good form
2	13.5	11.5	49	15	7.5	0.7	" "
3	10.5	7.5	20	7	3.5	-	" "
4	4.0	2.5	12	7	2.0	-	" "
5	16.0	14.5	44	12	6.5	-	" "
6	16.0	14.0	37	15	6.0	-	" "
7	15.5	12.0	36	16	6.0	-	" "
8	6.0	4.0	18	7	3.0	-	" "
9	14.0	12.0	45	12	6.5	-	" "
10	13.5	12.0	34	8	6.0	-	" "
11	5.5	4.0	11	7	2.0	0.9	" "
12	12.5	10.0	25	10	4.0	-	" "
13	3.5	2.0	11	7	1.5	-	" "
14	12.5	11.0	45	12	7.0	-	" "
15	12.0	8.5	30	15	7.5	-	Branched
16	11.5	8.5	25	7	4.0	-	good form
17	14.5	11.5	33	9	6.0	-	" "
18	11.0	9.0	21	7	3.5	-	" "
19	10.0	8.5	22	7	3.0	-	" "
20	15.5	13.0	45	7	6.0	-	" "

PHOTO PLOT.

Stratum 1d Occurence 8 Plot No. 9

Mean plot Height = 13.01 m Plot Area: 0.0583 ha.

Tree No.	Cd measured on photo (cm)	Crown diameter in m	Crown area m^2	Calculated dbh (cm)	Estimated vol. in m.
1	0.11	5.94	27.71	39	0.84
2	0.11	5.94	27.71	39	0.84
3	0.12	6.48	32.98	43	1.02
4	0.10	5.40	22.90	35	0.67
5	0.10	5.40	22.90	35	0.67
6	0.10	5.40	22.90	35	0.67
7	0.08	4.32	14.65	26	0.36
8	0.12	6.48	32.98	43	1.02
9	0.09	4.86	18.55	31	0.52
10	0.08	4.32	14.65	26	0.36
11	0.08	4.32	14.65	26	0.36
12	0.08	4.32	14.65	26	0.36
TOTAL			267.23		7.69

Crown cover per cent = 46

No. of trees per ha. = 206

Mean volume per tree = 0.6408

Volume per ha = 132.01

FIELD PLOT.

STRATUM 2d OCCURRENCE 12 PLOT NO. 1 PLOT AREA 0.06 ha.

TREE NO.	HEIGHT (m)		DIAMETER (cm)		CROWN DIAMETER (m)	INCREMENT FOR LAST FIVE YEARS (cm.)	CONDITION OF TRUNK AND CROWN
	TOTAL	TIMBER	DBH	TOP			
1	11	8.5	27	7	7	-	Good form
2	13.5	11.5	35	7	7.5	-	" "
3	13.5	10.5	43	18	10	-	" "
4	13	11	28	8	6	-	" "
5	13.5	8	43	10	10	-	Spreading crown
6	15.5	11	52	20	11	-	" "
7	12.5	8	15	7	5	-	" "
8	11	8.5	27	7	7	-	Good form
9	11	6.5	37	18	7.5	-	Spreading crown
10	12	9	26	7	6	-	Good form
11	9.5	7	35	17	8	-	Spreading crown
12	17	13.5	44	17	10	-	Good form
13	4.5	2.5	9	7	2	1.0	" "
14	8	5	17	7	4	-	" "
15	14.5	12	33	7	7	-	" "
16	13	11.5	85	20	18	0.7	Spreading crown
17	13	11.5	35	10	7	-	Good form

PHOTO PLOT.

Stratum 2d   Occurence 12   Plot No. 1

Plot Area 0.0583 ha   Mean Ht. 12.71

Tree No.	Cd measured measured on photo (cm)	Crown diameter (cd) in m	Crown Area m^2	Calculated dbh cm	Estimated vol. cum
1	0.11	5.94	27.71	39	0.84
2	0.13	7.02	38.7	47	1.23
3	0.10	5.40	22.9	35	0.67
4	0.11	5.94	27.71	39	0.84
5	0.11	5.94	27.71	39	0.84
6	0.10	5.40	22.90	35	0.67
7	0.11	5.94	27.71	39	0.84
8	0.11	5.94	27.71	39	0.84
9	0.09	4.86	18.55	31	0.52
10	0.08	4.32	14.65	26	0.36
11	0.08	4.32	14.65	26	0.36
12	0.08	4.32	14.65	26	0.36
13	0.09	4.86	18.55	31	0.52
14	0.08	4.32	14.65	26	0.36
15	0.08	4.32	14.65	26	0.36
16	0.08	4.32	14.65	26	0.36
TOTAL			348.05		9.97

Crown cover per cent = 60

No. of trees per ha = 275

Mean Volume per tree = 0.6231 cum

Volume per ha = 171.36 cum

FIELD PLOT.

STRATUM 3d OCCURENCE 11 PLOT NO. 6 PLOT AREA 0.166 ha.

TREE NO.	HEIGHT (m)		DIAMETER (cm)		CROWN DIAMETER (m)	INCREMENT FOR LAST FIVE YEARS (cm.)	CONDITION OF TRUNK AND CROWN
	TOTAL	TIMBER	DBH	TOP			
1	14.0	10.0	52	20	9.0	-	Spreading crown
2	15.5	12.5	41	15	8.0	-	Good form
3	16.0	12.5	62	20	10.0	-	Spreading crown
4	12.5	7.5	57	35	9.5	-	" "
5	11.0	8.5	41	16	6.0	-	" "
6	14.5	11.5	65	10	10.5	1.0	" "
7	18.0	15.0	54	12	7.5	-	" "
8	16.0	11.5	57	30	9.5	-	" "
9	13.5	9.5	38	12	6.0	0.9	" "

PHOTO PLOT.

Stratum 3d Occurence 11 Plot No. 6

Plot Area 0.175 ha. Mean Plot ht = 14.67 m

Tree No.	Cd measured on photo (cm)	Crown diameter (cd) in (m)	Crown Area (m^2)	Calculated dbh (cm)	Estimated Volume (cum)
1	0.15	8.10	51.53	55	1.69
2	0.17	9.18	66.19	63	2.22
3	0.13	7.02	38.70	47	1.23
4	0.12	6.48	32.98	43	1.02
5	0.11	5.94	27.71	39	0.84
6	0.11	5.94	27.71	39	0.84
7	0.13	7.02	38.70	47	1.23
8	0.11	5.94	27.71	39	0.84
9	0.10	5.4	22.90	35	0.67
10	0.10	5.4	22.90	35	0.67
TOTAL			357.03		11.25

Crown cover per cent = 20

No. of trees per ha = 58

Mean tree volume = 1.125 cum

Volume per ha = 65.25 cum

FIELD PLOT.

STRATUM 4d OCCURENCE 10 PLOT NO. 1 PLOT AREA 0.2 ha

TREE NO.	HEIGHT (m)		DIAMETER (cm)		CROWN DIAMETER (M)	INCREMENT FOR LAST FIVE YEARS (cm.)	CONDITION OF TRUNK AND CROWN
	TOTAL	TIMBER	DBH	TOP			
1	11.0	9.0	39	20	6.5	-	Good form
2	12.5	10.0	48	20	7.0	-	" "
3	10.5	8.5	46	20	9.0	-	Spreading crown
4	11.0	8.5	34	10	8.0	-	" "
5	11.5	9.0	49	25	9.5	0.5	" "
6	9.0	7.0	28	15	6.0	-	" "
7	11.5	8.0	49	30	9.5	-	" "
8	12.5	10.5	44	15	7.0	-	Good form
9	10.0	5.0	22	12	5.0	0.3	Spreading crown
10	13.0	10.0	42	8	6.5	-	Good form

PHOTO PLOT.

Stratum 4d | Occurence 10 | Plot No. 1

Plot Area 0.204 ha | Mean plot height = 11.67 m

Tree No.	Cd measured on photo (cm)	Crown diameter (cd) (m)	Crown area (m^2)	Calculated dbh (cm)	Estimated Volume (cum)
1	0.14	7.56	44.89	51	1.45
2	0.10	5.40	22.90	35	0.67
3	0.10	5.40	22.90	35	0.67
4	0.10	5.40	22.90	35	0.67
5	0.15	8.10	51.53	55	1.69
6	0.12	6.48	32.98	43	1.02
7	0.17	9.18	66.19	63	2.22
8	0.11	5.94	27.71	39	0.84
9	0.12	6.48	32.98	43	1.02
10	0.13	7.02	38.70	47	1.23
TOTAL			363.68		11.48

Crown cover per cent = 18

No. of trees per ha = 49

Mean tree volume = 1.148 cum

Volume per ha = 56.25 cum

FIELD PLOT.

STRATUM 5d OCCURENCE 25 PLOT NO. 1 PLOT AREA 0.3 ha.

TREE NO.	HEIGHT (m)		DIAMETER (cm)		CROWN DIAMETER (m)	INCREMENT FOR LAST FIVE YEARS (cm.)	CONDITION OF TRUNK AND CROWN
	TOTAL	TIMBER	DBH	TOP			
1	10	8	26	12	5.5	-	Spreading crown
2	16	1.5	107	50	14	0.9	started tree at 1.5 m ht.
		9	50	10			
3	12	10	34	10	6	-	Spreading crown
4	9.5	5	31	18	6.5	-	" "
5	8.5	5	19	15	3	-	" "
6	10	5.5	32	28	7.5	-	" "
7	12	10	44	15	10	-	" "
8	6.5	4.5	17	7	4	1.5	Good form
9	12.5	8	32	10	6.5	-	Spreading crown

PHOTO PLOT.

Stratum 5d | Occurence 25 | Plot No. 1

Plot Area 0.2916 ha | Mean plot height = 11.01

Tree No.	Cd Measured on photo (cm)	Crown diameter (m) (cd)	Crown Area (m^2)	Calculated dbh (cm)	Estimated Volume (cum)
1	0.27	14.58	166.96	104	6.37

Crown cover per cent = 6

No. of trees per ha = 4

Volume per ha = 19,31 cum

FIELD PLOT.

STRATUM 1f OCCURENCE 1 PLOT NO. 4 PLOT AREA 0.0314 ha.

TREE NO.	HEIGHT (m)		DIAMETER (cm)		CROWN DIAMETER (m)	INCREMENT FOR LAST FIVE YEARS (cm.)	CONDITION OF TRUNK AND CROWN
	TOTAL	TIMBER	DBH	TOP			
1	17.0	13.5	36	12	5.0	-	Good form
2	18.5	16.0	37	7	5.0	-	" "
3	17.0	12.5	30	20	4.0	0.45	Spreading crown
4	17.5	14.5	44	12	7.0	-	Good form
5	17.0	14.5	49	15	7.5	0.60	" "
6	18.5	15.0	37	10	5.5	-	" "
7	18.5	16.5	45	16	7.0	-	" "
8	16.0	14.0	43	12	6.5	-	" "
9	17.0	13.50	42	20	7.0	-	" "
10	16.5	13.5	42	13	6.5	-	" "

PHOTO PLOT.

Stratum 1f Occurence 1 Plot No. 4

Plot Area 0.0292 ha Mean plot height 15.94 m.

Tree No.	Cd Measured on photo	Crown diameter (cd)(m)	Crown Area (m^2)	Calculated dbh (cm)	Estimated Volume (cum)
1	0.11	5.94	27.71	39	1.06
2	0.12	6.49	32.98	43	1.29
3	0.11	5.94	27.71	39	1.06
4	0.10	5.40	22.90	35	0.84
5	0.09	4.86	18.55	31	0.66
6	0.09	4.86	18.55	31	0.66
7	0.08	4.32	14.65	26	0.45
8	0.08	4.32	14.65	26	0.45
9	0.10	5.40	22.90	35	0.84
10	0.10	5.40	22.90	35	0.84
TOTAL			223.50		8.15

Crown cover per cent = 77

Number of trees per ha = 343

Mean tree volume = 0.8150 cum

Volume per ha = 279.55 cum

APPENDIX B. Preliminary Estimation of Volume in photo plots.

Stratum 1d.

Plot No.	Stand Volume (m^3 ha^{-1})	Plot No.	Stand Volume (m^3 ha^{-1})
1	145.08	27	166.77
2	106.39	28	188.83
3	138.00	29	188.66
4	127.26	30	175.34
5	202.23	31	100.01
6	134.84	32	225.09
7	265.98	33	130.41
8	151.43	34	142.01
9	175.07	35*	132.01
10	130.17	36*	226.38
11	117.47	37*	206.35
12	101.56	38	231.61
13	61.25	39	206.93
14	166.63	40	181.66
15	116.17	41	154.10
16	193.11	42	135.45
17	259.65	43	128.41
18	168.07	44	205.16
19	167.55	45	245.74
20	179.39	46	152.15
21	249.36	47	141.39
22	171.84	48	135.76
23	107.90	49	205.50
24*	241.60	50	172.82
25*	215.79	51	201.89
26	181.93	52	216.09

*Selected for Field measurements.

APPENDIX (cont.)

Stratum 2d.

Plot No.	Stand Volume (m^3 ha^{-1})	Plot No.	Stand Volume (m^3 ha^{-1})
1	139.86	27	188.54
2	170.28	28	188.03
3	205.16	29	186.53
4	104.41	30	153.18
5	271.99	31	223.03
6	183.39	32	171.08
7	117.75	33	152.77
8	166.63	34	115.92
9	90.13	35	105.85
10	213.09	36	139.05
11	74.37	37	116.84
12	132.31	38	245.44
13	184.03	39	162.15
14	122.04	40	171.36
15	199.86	41	148.72
16	99.47	42	183.08
17	74.57	43	123.69
18	112.20	44	129.17
19	143.25	45	148.97
20	146.46	46	117.30
21	257.66	47	123.28
22	157.61	48	172.00
23	110.92	49	179.57
24	100.70	50	139.15
25	151.66	51	149.64
26	163.60	52	193.45
		53	136.74

APPENDIX (cont.)

Stratum 3d.

Plot No.	Stand Volume (m^3 ha^{-1})	Plot No.	Stand Volume (m^3 ha^{-1})
1	140.20	32	82.59
2	83.74	33	47.44
3	221.53	34	154.28
4	105.32	35	101.20
5	148.58	36	81.55
6*	120.51	37	66.99
7	128.61	38	130.41
8	131.07	39	140.61
9	130.34	40	79.52
10	166.67	41	101.43
11	79.61	42	151.89
12	187.14	43	207.89
13*	132.72	44	199.41
14	112.24	45*	78.42
15	70.14	46	217.50
16	129.67	47*	65.25
17	191.61	48	125.81
18	79.94	49	154.20
19	37.87	50	213.97
20	86.71	51*	107.04
21	58.28	52	79.14
22	86.44	53	147.00
23	49.44	54	67.48
24	60.20	55	96.22
25	124.18	56	135.93
26	112.88	57	73.49
27*	96.87	58	148.72
28	108.19	59	104.52
29*	102.13	60	151.80
30	136.31	61	182.66
31	83.13	62	165.06
		63	118.45

APPENDIX (Cont.)

Stratum 4d:

Plot No.	Stand Volume (m^3 ha^{-1})	Plot No.	Stand Volume (m^3 ha^{-1})
1	113.74	26	88.67
2*	170.62	27	78.28
3	150.64	28	67.55
4	132.01	29	31.09
5	61.45	30	41.89
6	106.20	31	53.36
7	82.32	32	83.95
8*	67.06	33	97.03
9	94.31	34*	56.25
10	133.88	35*	98.39
11	111.97	36	80.17
12	84.44	37	75.56
13	141.29	38	51.71
14	140.34	39	61.51
15	71.95	40	94.08
16	61.36	41	93.61
17	78.42	42	82.53
18	80.85	43	87.23
19	68.99	44	107.50
20	64.16	45	75.63
21	103.47	46	87.96
22	75.98	47	71.92
23	138.63	48	82.56
24*	149.21	49	53.45
25	130.20		

APPENDIX (Cont.)

Stratum 5d:

Plot No.	Stand Volume (m^3 ha^{-1})	Plot No.	Stand Volume (m^3 ha^{-1})	Plot No.	Stand Volume (m^3 ha^{-1})
1	92.68	28	30.52		
2	45.15	29	39.67	55	31.47
3	114.42	30	43.89	56	54.04
4	81.33	31	50.33	57	37.58
5	51.25	32	34.93	58	26.64
6	64.90	33	58.54	59	75.26
7	42.14	34	50.51	60	57.54
8*	114.84	35	30.14	61	69.29
9	39.41	36	30.10	62	45.46
10	73.85	37	74.07	63	34.97
11	56.16	38	44.98	64	43.68
12	62.38	39	131.92	65	29.26
13	50.54	40	38.40	66	27.86
14	75.37	41	41.93	67	65.93
15	70.98	42*	60.38	68	40.01
16	50.83	43	32.13	69	56.49
17	28.56	44	13.16	70*	62.37
18	21.70	45	20.94	71	44.80
19	56.69	46	51.75	72	43.68
20	56.37	47	33.86	73	39.28
21	32.36	48*	76.69	74	66.68
22	49.70	49	59.21	75	62.60
23	64.48	50	52.82	76	36.89
24	44.54	51	81.83	77*	19.31
25	69.61	52	38.29	78*	38.61
26	31.82	53	51.20	79*	37.14
27	58.00	54*	43.34		

APPENDIX (Cont.)

Stratum 1f:

Plot No.	Stand Volume ($m^3\ ha^{-1}$)	Plot No.	Stand Volume ($m^3\ ha^{-1}$)
1	228.19	27*	441.37
2	396.76	28	383.77
3	450.92	29	366.75
4	342.17	30	228.66
5	396.75	31	293.27
6	255.36	32	353.63
7	334.03	33	295.73
8	216.86	34*	203.74
9	550.35	35	322.06
10	239.41	36	332.37
11	208.46	37	255.65
12	350.20	38	306.30
13	306.24	39	244.90
14	205.30	40	365.99
15	299.75	41.	372.69
16	296.74	42	221.07
17	302.13	43	287.43
18	453.54	44	334.43
19*	279.55	45	327.40
20	365.64	46	330.94
21	345.74	47	348.49
22*	341.85		
23	242.00		
24	299.45		
25	247.65		
26	254.72		

APPENDIX C.

The statistics heading to an estimate of mean photo volume and its variance and confidence limits for each Stratum.

Stratum 1d.

Number of photo samples N = 52

Sum of 52 photo plot volumes $= \Sigma \text{ pvol} = 8872.18$

Mean photo volume per ha $= \frac{\Sigma \text{ pvol}}{52} = 170.62$ cum

The variance of mean photo volume

$$= s^2 = \frac{\Sigma(\text{pvol})^2 - \frac{(\Sigma \text{pvol})^2}{N}}{N - 1}$$

Sum of the squared photo volumes

$$\Sigma(\text{pvol})^2 = 1622211.80$$

The square of the sum of photo volumes by N

$$= \frac{(\Sigma \text{pvol})^2}{N} = 1513761.11$$

$$s^2 = \frac{1622211.80 - 1513761.11}{51} = 2126.48$$

The standard error ($S_{\bar{n}}$) of the mean

$$= \sqrt{\frac{s^2}{N}} = 6.39$$

Confidence Limits (C.L.) $= S_{\bar{x}} .t = 12.79$

where t = 2.0000 at 95% probability

and 51 degrees of freedom = 7.49% of the mean

Stratum 2d.

N = 53

Σ pvol = 815.93

Mean volume per ha = 153.92 cu m

$$s^2 = \frac{\Sigma(\text{pvol})^2 - \frac{(\Sigma \text{pvol})^2}{N}}{N - 1}$$

APPENDIX C (cont).

$$\Sigma(\text{pvol})^2 = 1353025.31$$

$$\frac{(\Sigma \text{pvol})^2}{53} = 1255694.75$$

$$s^2 = \underline{\underline{1871.74}}$$

The Standard error $= \sqrt{\frac{s^2}{N}} = 5.9427$

Confidence limit (C.L.) $= \underline{\underline{11.8854}}$

t = 2.00 at 95% probability and

52 degrees of freedom

= <u>7.72%</u> of the mean.

Note: All Symbols and formulae throughout this appendix will be used as described in stratum 1d.

<u>Stratum 3d.</u>

$N = 63$

$\Sigma \text{pvol} = 7480.14$

Mean Volume per ha = <u>118.73</u> cu m

$$\Sigma(\text{pvol})^2 = 1013938.06$$

$$\frac{(\Sigma \text{pvol})^2}{63} = 888134.83$$

$$s^2 = 2029.08$$

Standard error $= \sqrt{\frac{2029.08}{63}} = 5.6752$

C.L. $= 2 \times 5.6752 = \underline{\underline{11.35}}$

where t = 2 at 95% probability and 62 d = <u>9.56%</u> of the mean.

<u>Stratum 4d.</u>

$N = 49$

$\Sigma \text{pvol} = 4415.37$

Mean Volume per ha = <u>90.10</u> cu m.

APPENDIX C (cont)

$\sum(\text{pvol})^2 = 443971.94$

$\frac{(\sum \text{pvol})^2}{49} = 397867.19$

$s^2 = 940.91$

Standard error $= \sqrt{\frac{940.91}{49}} = \underline{\underline{4.38}}$

C.L. $= 2 \times 4.38 = \underline{\underline{8.76}}$

$= 9.72\%$ of the mean.

Stratum 5d.

$N = 79$

$\sum \text{pvol} = 4062.45$

Mean volume per ha $= \underline{\underline{51.42}}$ cu m

$\sum(\text{pvol})^2 = 244777.37$

$\frac{(\sum \text{pvol})^2}{79} = 208905.06$

$s^2 = 459.90$

Standard error $= \sqrt{\frac{459.90}{79}} = \underline{\underline{2.41}}$

C.L. $= 2.41 \times 2 = \underline{\underline{4.82}}$

$= \underline{\underline{9.38\%}}$ of the mean.

Stratum 1f.

$N = 47$

$\sum \text{pvol} = 14826.40$

Mean Volume per ha $= \underline{\underline{315.46}}$ cu m

$\sum(\text{pvol})^2 = 4927507.91$

$\frac{(\sum \text{pvol})^2}{47} = 4677066.74$

$s^2 = 5444.37$

Standard error $= \sqrt{\frac{5444.37}{47}} = \underline{\underline{10.76}}$

C.L. $= 10.76 \times 2 = \underline{\underline{21.52}}$

$= 6.82\%$ of the mean.

Appendix D. Calculation of Volume and other parameters for field and photo plots for each stratum.

Stratum 1d Area = 387.50 ha No. of PHOTO PLOTS = 52

Occ. No.	Plot No.	Photo Ht. (m)	Ground Ht. (m) Lorey's	Ground Ht. (m) Top Ht.	Density: No. trees / ha photo	Density: No. trees / ha ground	Density: crown cover % photo	Density: crown cover % ground	Stand vol/ha m^3 Photo	Stand vol/ha m^3 Ground	Photo Volumes from photo Hts. (m^3 ha^{-1})*	Photo & ground plot area (ha)
8	9	13.01	13.54	14.00	206	343	46	73	132.01	168.97	126.01	0.0583
8	10	15.99	14.62	16.17	343	446	77	83	226.38	244.68	246.96	0.02916
8	11	15.27	15.37	16.50	189	326	66	80	266.35	252.16	215.29	0.0583
20	2	15.41	15.15	15.58	160	251	73	109	241.60	212.75	262.86	0.0875
20	3	16.18	18.33	19.50	206	309	69	70	215.79	161.43	234.48	0.0583
	MEAN	15.17	15.40	16.35	221	335	62	83	204.43	208.00	217.12	

* Using Hamilton 1975.

Stratum 2d Area: 137.33 ha No. PHOTO PLOTS = 53

Occ. No.	Plot No.	Photo Ht. (m)	Ground Ht. (m) Lorey's	Ground Ht. (m) Top Ht.	Density: No. Trees / ha photo	Density: No. Trees / ha ground	Density: crown cover % photo	Density: crown cover % ground	Stand vol/ha m^3 Photo	Stand vol/ha m^3 Ground	Photo Volumes from photo Hts. (m^3 ha^{-1})*	Photo & ground plot area (ha)
12	1	12.71	13.23	13.40	275	283	60	86	171.36	190.93	156.06	0.0583
13	1	12.19	10.87	11.17	112	154	47	54	153.18	74.23	139.57	0.1166
2	1	16.41	18.06	18.43	49	49	22	29	69.48	116.69	78.6	0.02041
2	2	14.51	15.71	17.25	58	115	44	45	152.77	134.62	159.27	0.1750
9	2	14.93	13.44	14.06	172	200	55	109	170.28	179.69	159.96	0.0583
MEAN		14.15	14.26	14.86	134	161	45.6	80	143.41	139.23	138.69	

Stratum 3d Area = 91.74 ha TOTAL NO. OF PHOTO PLOTS = 63

Occ. No.	Plot No.	Photo Ht. (m)	Ground Ht. (m) Lorey's	Ground Ht. (m) Top Ht.	Density: No. Trees / ha photo	Density: No. Trees / ha ground	Density: crown cover % photo	Density: crown cover % ground	Stand vol/ha m^3 Photo	Stand vol/ha m^3 Ground	Photo Volumes from photo Hts. (m^3 ha^{-1})*	Photo & ground plot area (ha)
11	6	14.67	14.79	14.56	58	55	20	31	65.25	74.49	67.98	0.1700
11	4	19.11	19.59	21.17	59	61	24	23	78.42	109.97	95.33	0.2041
13	1	14.88	14.60	14.33	59	69	32	47	107.04	71.41	111.51	0.2041
3	6	15.18	16.90	16.56	28	28	39	27	120.51	86.50	125.79	0.2916
8	13	14.08	14.24	12.72	35	42	43	48	132.72	101.62	132.72	0.2916
15	1	10.96	12.69	12.67	59	69	21	38	66.68	80.68	58.12	0.2041
10	1	15.43	16.95	16.78	42	54	41	51	141.50	131.27	154.90	0.2624
		14.90	15.68	15.54	48.57	54	31.43	38	101.73	93.71	106.62	

Stratum 4d   Area = 69.27 ha   Total No. of PHOTO PLOTS = 49

Occ. No.	Plot No.	Photo Ht. (m)	Ground Ht. (m) Lorey's	Ground Ht. (m) Top Ht.	Density No. Trees / ha photo	Density No. Trees / ha ground	Density crown cover % photo	Density crown cover % ground	Stand vol/ha m^3 Photo	Stand vol/ha m^3 Ground	Photo Volumes from photo Hts. (m^3 ha^{-1})*	Photo & ground plot area (ha)
1	8	14.14	14.86	14.58	28	31	20	10	67.06	33.83	67.06	0.2916
15	2	15.02	16.88	16.67	48	26	20	22	65.80	71.62	69.91	0.2333
7	1	10.12	10.35	9.00	35	48	16	15	53.45	18.40	44.10	0.2916
4	5	12.29	13.16	11.92	86	86	45	35	149.21	72.19	136.05	0.1166
9	1	13.95	11.86	11.86	42	42	26	34	88.26	46.75	88.26	0.2624
10	1	11.67	11.54	11.25	49	50	18	22	56.25	35.59	48.89	0.2041
		12.87	13.11	12.55	48	48	24	23	80.01	46.40	75.71	

Stratum 5d   Area = 151.79 ha   TOTAL NO. OF PHOTO PLOTS = 72

Occ. No.	Plot No.	Photo Ht. (m)	Ground Ht. (m) Lorey's	Ground Ht. (m) Top Ht.	Density No. Trees / ha photo	Density No. Trees / ha ground	Density crown cover % photo	Density crown cover % ground	Stand vol/ha m^3 Photo	Stand vol/ha m^3 Ground	Photo Volumes from photo Hts. (m^3 ha^{-1})*	Photo & ground plot area (ha)
1	8	15.05	15.20	14.23	58	63	34	22	114.84	92.31	119.77	0.1750
17	1	12.95	12.95	12.63	28	28	18	19	60.38	45.63	57.65	0.2916
6	1	9.72	10.49	9.44	28	31	22	20	76.69	28.71	51.21	0.2916
13	1	13.77	12.23	11.95	52	42	19	19	62.37	63.97	62.37	0.2916
25	7	15.48	16.75	15.75	11	14	11	15	37.14	42.46	43.19	0.2916
25	5	12.09	13.87	12.90	7	18	12	20	38.61	69.00	35.98	0.2916
25	1	11.01	13.99	10.78	4	30	6	14	19.31	46.60	19.60	0.2916
		12.87	13.64	12.53	27	33	17	18	58.48	55.53	55.68	

Stratum 1F. Area = 184.19 ha. Total No. of PHOTO PLOTS = 47.

			Ground Ht. m		Density				Stand Vol/ha m^3		
					No. trees / ha		Crown cover %				Plot Area
Occ. No.	Plot No.	Photo HT. m	Lorey's Mean Ht.	Top Ht.	Photo	Ground	Photo	Ground	Photo	Ground	ha.
8	1	18.18	20.85	21.50	343	380	60	83	203.74	242.26	0.0292
1	4	15.94	17.32	17.17	343	319	77	96	279.55	333.80	0.0292
1	12	21.10	18.28	18.83	583	445	12	96	441.37	365.96	0.0292
1	7	20.98	19.04	18.90	481	411	96	134	341.85	484.35	0.0292
12	7	21.55	18.91	20.25	412	414	86	71	307.96	495.29	0.0292
		19.75	18.88	19.33	432	394	88	94	314.89	444.33	

APPENDIX E.

Estimated values of ground volume per hectare for the 301 photo plots of the five d-type Strata derived from their photo crown cover percent by using the formula =

$$GVOL = 2.85\ PCC + 2.59 \quad \text{(Section 4.23)}$$

where GVOL = Ground volume ($m^3\ ha^{-1}$)

PCC = photo crown cover percent.

Stratum 1d (Total 52 photo plots)

Photo Crown Cover % (PCC)	GVOL. (Calc) (m^3 ha^{-1})	PCC % x 1	GVOL. (Calc) (m^3 ha^{-1}) (x)
49	142.2377	39	113.74
37	108.04	55	159.34
44	127.99	50	145.09
41	119.44	55	159.34
63	182.14	61	176.44
43	125.14	55	159.34
85	244.84	32	93.79
60	173.59	74	213.49
56	162.19	41	119.44
42	122.29	43	125.14
36	105.19	73	210.64
32	93.79	62	179.29
19	56.74	63	182.14
57	165.04	48	139.39
36	105.19	41	119.44
68	196.39	40	116.59
87	250.54	67	193.54
62	179.29	74	213.49
55	159.34	45	130.84
65	187.84	42	122.29
84	241.99	43	125.14
* 66	190.69	77	222.04
* 77	222.04	69	199.24
* 46	133.69	64	184.99
69	199.24	89	256.24
73	210.64		
63	182.14		

* ground plots.

Stratum 2d. (54 photo plots).

PCC %	GVOL. (Calc.) (m^3 ha^{-1})	PCC %	GVOL. (Calc.) (m^3 ha^{-1})	PCC %	GVOL. (Calc.) (m^3 ha^{-1})
*55	159.34	32	93.79	69	199.24
*22	65.29	30	88.09	45	130.84
*60	173.59	45	130.84		
*44	127.99	47	136.54		
*47	136.54	58	167.89		
45	130.84	57	165.04		
61	176.44	58	167.89		
33	96.64	72	207.79		
84	241.99	50	145.09		
56	162.19	40	116.59		
38	110.89	32	93.79		
51	147.94	43	125.14		
29	85.24	37	108.04		
70	202.69	76	219.19		
23	68.14	51	147.94		
41	119.44	45	130.84		
55	159.34	55	159.34		
40	116.59	39	113.74		
58	167.89	40	116.59		
30	88.09	50	145.09		
24	70.99	40	116.59		
34	99.49	39	113.74		
42	122.29	55	159.34		
45	130.84	57	165.04		
78	224.89	44	127.99		
47	136.54	49	142.24		

* Ground plots.

Stratum 3d = (65 photo plots).

PCC %	GVOL. (Calc.) (m^3 ha^{-1})	PCC %	GVOL. (Calc.) (m^3 ha^{-1})	PCC %	GVOL. (Calc.) (m^3 ha^{-1})
*20	59.59	39	113.74	44	127.99
*24	70.99	23	68.14	33	96.64
*32	93.79	42	122.29	23	68.14
*43	125.14	31	90.94	22	65.29
*39	113.74	47	136.54	39	113.74
*41	119.44	58	167.89	43	125.14
*21	62.44	51	147.94	22	65.29
47	136.54	39	113.74	30	88.09
26	76.69	40	116.59	47	136.54
66	190.69	61	176.44	67	193.54
34	99.49	25	73.84	57	165.04
46	133.69	13	39.64	70	202.09
37	108.64	26	76.69	40	116.59
39	113.74	17	51.04		
39	113.74	26	76.69		
54	156.49	15	45.34		
25	73.84	17	51.04		
59	170.74	38	110.89		
36	105.19	32	93.79		
20	59.59	29	85.24		
47	136.54	31	90.94		
67	193.54	30	88.09		
25	73.84	43	125.14		
18	53.89	24	70.99		
20	59.59	26	76.69		
29	85.24	15	45.34		

* Ground plots.

Stratum 4d (51 photo plots)

PCC %	GVOL.(Calc.) (m^3 ha^{-1})	PCC %	GVOL.(Calc.) (m^3 ha^{-1})
37	108.04	28	82.39
56	162.19	25	73.84
46	133.69	22	65.29
40	116.59	11	33.94
19	56.74	13	39.64
31	90.94	17	51.04
24	70.99	26	76.69
27	79.54	31	90.94
40	116.59	29	85.24
33	96.64	26	76.69
26	76.69	26	76.69
42	122.29	16	48.19
41	119.44	19	56.74
22	65.29	28	82.39
27	79.54	31	90.94
22	65.29	25	73.84
26	76.69	26	76.69
19	54.74	33	96.64
24	70.99	23	68.14
24	70.99	*18	53.89
20	59.59	*45	130.84
19	56.74	*16	48.19
30	88.09	*20	59.59
22	65.29	*26	76.69
45	130.84	*20	59.59
39	113.74		

* Ground plots.

Stratum 5d. (79 photo plots)

PCC %	GVOL. (Calc.) (m^3 ha^{-1})	PCC %	GVOL. (Calc.) (m^3 ha^{-1})	PCC %	GVOL. (Calc.) (m^3 ha^{-1})
*22	65.29	15	45.34	8	25.39
*18	53.89	11	33.94	11	33.94
*19	54.74	14	42.49	13	39.64
*34	99.49	9	28.24	15	45.34
* 6	19.69	9	28.24	10	31.09
*12	36.79	21	62.44	18	53.89
*11	33.94	12	36.79	15	45.34
28	82.39	16	48.19	9	28.24
14	42.49	13	39.64	10	31.09
36	105.19	13	39.64	23	68.14
23	68.14	11	33.94	14	42.49
16	48.19	20	59.59	9	28.24
19	56.74	20	59.59	12	36.79
12	36.79	13	39.64	12	36.79
12	36.79	15	45.34	10	31.09
22	65.29	8	25.39	4	13.99
17	51.04	7	22.54	8	25.39
20	59.59	17	51.04	16	48.19
15	45.34	17	51.04	11	33.94
21	62.44	9	28.24	18	53.89
22	65.29	14	42.49	16	48.19
12	36.79	19	56.74	24	70.99
8	25.39	14	42.49	12	36.79
22	65.29	20	59.59	15	45.34
17	51.04	10	31.09	12	36.79
23	68.14	17	51.04	9	28.24
				16	48.19

* Ground plots.

APPENDIX F.

Calculations of Strata Means, variances and confidence limits for the data shown in Appendix E.

STRATUM 1d.

Volume:-

Number of plots "N" = 52

Σ GVOL = 8448.13

$(\Sigma \text{GVOL})^2$ = 71370900.50

$\Sigma (\text{GVOL})^2$ = 1479806.56

Variance S^2 $= \dfrac{\Sigma \text{GVOL}^2 - (\Sigma \text{GVOL})^2/N}{N - 1}$

S^2 = 2103.7083

Standard deviation "S" $= \sqrt{S^2}$ = 45.8662

Standard error $(S_{\bar{x}})$ $= \sqrt{\dfrac{S^2}{N}}$ = 6.3605

Confidence limit (C.L.) $= S_{\bar{x}} \cdot t$

= 12.7210

where t = 2.00 at P0.05

C.L. = 7.83% of the mean

Total Stratum volume = area x mean

= 387.5 x 162.46

= 62953.25 m^3

Photo Crown Cover:-

Σ PCC = 2917

MEAN PCC = 56.1%

$(\Sigma \text{PCC})^2$ = 8508903

$\Sigma (\text{PCC})^2$ = 176843.00

Variance $(S^2 \text{pcc})$ = 259.0245

$S_{\bar{x}}$ $= \sqrt{\dfrac{S^2}{N}}$ = 2.2319

C.L.	=	$S_{\bar{x}} \cdot t$ = 4.4638
	=	7.96% of the mean.

STRATUM 2d.

Volume:-

N	=	54
$\sum$ GVOL	=	7655.81
Mean GVOL	=	138.67 m^3 ha^{-1}
$\sum (GVOL)^2$	=	1112110.21
$(\sum GVOL)^2$	=	55589102.76
S^2	=	1560.0449
$S_{\bar{x}}$	=	5.3749
C.L.	=	10.7498 (where t = 2 at P0.05)
	=	7.79% of the mean
Total Stratum Volume	=	Area x mean
	=	137.33 x 138.07
	=	18961.15 m^3

Photo Crown Cover:-

$\sum$ PCC	=	2567
Mean PCC	=	47.54
$\sum (PCC)^2$	=	132207
$(\sum PCC)^2$	=	6589489
Variance S^2pcc	=	192.0646
$S_{\bar{x}}$	=	1.8859
C.L.	=	3.7718 = 7.93% of the mean.

STRATUM 3d.

Volume:-

N	=	65
Σ GVOL	=	6806
Mean GVOL	=	104.71 m^3 ha^{-1}
$\Sigma (GVOL)^2$	=	818615.94
$(\Sigma GVOL)^2$	=	46321636.00
s^2	=	1655.8654
$S_{\bar{x}}$	=	5.0473
C.L.	=	10.0946 (t = 2)
	=	9.64% of the mean
Total Stratum Volume	=	Area x mean
	=	91.74 x 104.71
	=	9606.10

Photo Crown cover:

Σ PCC	=	2329
MEAN	=	35.83%
$\Sigma (PCC)^2$	=	96497
$(\Sigma PCC)^2$	=	5424241.00
s^2_{pcc}	=	203.86
C.L.	=	3.5420 (t = 2)
	=	9.89% of the mean.

STRATUM 4d.

Volume:-

N	=	51
Σ GVOL	=	4124.94
Mean Vol.	=	80.88 m^3 ha^{-1}

$\Sigma(GVOL)^2$	=	369472.20
$(\Sigma GVOL)^2$	=	17015130.0036
S^2	=	716.8440
$S_{\bar{x}}$	=	3.7491
C.L.	=	7.4982 ($t = 2$)
	=	9.27% of the mean
Total Stratum Vol.	=	69.27 x 80.88 = 5602.56 m^3

Photo Crown Cover:-

Σ PCC	=	1401
Mean PCC	=	27.47%
$\Sigma(PCC)^2$	=	42899
$(\Sigma PCC)^2$	=	1962801
S^2_{pcc}	=	88.2541
$S_{\bar{n}}pcc$	=	1.3155
C.L.	=	2.6310 ($t = 2$)
	=	9.58% of the mean.

STRATUM 5d.

Volume:-

N	=	79
Σ GVOL	=	3610.36
MEAN	=	45.70 m^3 ha^{-1}
$\Sigma(GVOL)^2$	=	186689.23
$(\Sigma GVOL)^2$	=	13036499.3296
S^2	=	278.1158
$S_{\bar{x}}$	=	1.8763
C.L.	=	3.7526 ($t = 2$)
	=	8.21% of the mean.

Total Stratum Volume $= 151.79 \times 45.7$

$= \underline{6936.80}\ m^3$

Photo Crown Cover:-

Σ PCC $= 1195$

Mean PCC $= \underline{15.13\%}$

$\Sigma(PCC)^2 = 20747$

$(\Sigma PCC)^2 = 1428025.00$

$s^2_{pcc} = 34.2462$

$s_{\bar{x}} = 0.6583$

C.L. $= 1.3166\ (t = 2)$

$= \underline{8.7\%}$ of the mean

APPENDIX G.

Method of the calculation of t for Comparison of two means.

To test the hypothesis that there is no difference between two means (Referred to as a null hypothesis), t is computed as follows:-

$$t = \frac{\bar{X}_A - \bar{X}_B}{\sqrt{S^2 \frac{(n_A + n_N)}{(n_A)(n_B)}}}$$

where $\bar{X}_A$ and $\bar{X}_B$ = the arithmatic means for groups A and B

n_A and n_B = The number of observations in groups A and B (n_A and n_B do not have to be the same).

S^2 = The pooled within-group variance calculated as follows:-

$$S^2 = \frac{SS_A + SS_B}{(n_A-1) + (n_B-1)}$$

where SS_A and SS_B are the corrected sum of squares within group A and B.

This value of t has $(n_A-1) + (n_B-1)$ degrees of freedom.

Appendix H Diameters at breast height (DBH) and Volumes (of good form trees and branched trees (taken from ground measurements of the six strata)

Good form trees		Branched trees		Good form trees		Branched trees		Good form trees		Branched trees	
DBH (cm)	VOL. (cum)	DBH (cm)	VOL. (cum)	DBH (cm)	VOL. (cum)	DBH (cm)	VOL. (cum)	DBH (cm)	VOL. (cum)	DBH (cm)	VOL. (cum)
34	0.5269	45	0.6259	32	0.8113	62	1.8332	38	0.9505	35	0.3190
19	0.1935	97	4.1453	41	1.0898	31	0.3207	41	1.0868	23	0.1924
22	0.2406	65	3.2672	45	1.1921	42	0.8920	55	1.6485	30	0.3407
24	0.2889	45	0.9762	30	0.4287	47	0.9977	65	1.9976	24	0.2122
23	0.2156	43	0.6124	50	1.7085	62	2.0831	36	0.5759	54	0.9734
26	0.3922	52	1.3409	40	0.8963	65	1.9532	54	1.6335	61	1.8597
33	0.7001	15	0.0864	29	0.3328	54	1.8030	75	3.1015	21	0.1733
17	0.2008	37	0.4319	34	0.8554	57	1.8739	70	2.8178	71	2.4817
26	0.4067	35	0.4162	28	0.5328	54	2.1627	94	5.1597	58	2.0692
31	0.5753	85	3.4437	43	0.8957	60	2.1687	38	1.0066	68	2.5049
37	0.6573	38	0.4549	38	0.5920	100	3.7834	37	1.0266	78	4.0838
49	1.1862	41	0.7762	40	0.8246	82	4.3774	33	0.6789	77	4.1992
20	0.1322	40	0.5289	52	1.0212	85	3.0682	43	1.2298	55	1.9148
12	0.0189	55	1.1489	59	2.5471	70	2.5055	29	0.6348	68	2.2854
44	1.1847	57	1.7497	51	1.6744	64	2.2061	27	0.4887	67	1.9074
18	0.0585	61	2.0478	77	4.3496	54	1.4236	32	0.6319	66	1.2788
45	1.0218	41	0.6116	59	2.4016	89	2.9408	35	0.9105	52	1.1505
34	0.5748	68	2.8568	48	1.4903	51	0.9435	39	0.9870	56	1.3191
25	0.2848	73	2.5872	56	2.2216	82	2.8443	40	1.0458	84	2.3199
45	0.9367	61	2.4792	54	1.5419	64	1.5696	49	1.4955	75	1.7063
42	1.0153	35	0.4424	71	3.8356	72	2.1503	45	1.3765	60	1.3349
47	1.3384	75	3.3123	56	2.1603	49	0.9429	42	1.1468	55	0.6434
21	0.2079	44	0.4588	53	1.8554	41	0.4902	45	1.4599	46	0.7410
38	0.7794	57	1.7196	26	0.2135	95	3.8836	34	0.9125	35	0.3763
17	0.1726	51	1.5289	57	2.4332	58	1.4780	37	1.0670	81	1.2294
								46	1.3179	79	2.0865

APPENDIX I.

Data For Increment Calculations:-

Stratum	DBH_1 (1982)(cm)	DBH_0 (1977)(cm)	$(DBH_1)^2$ (1982)cm^2	$(DBH_0)^2$ (1971)cm^2
1d	97	95.6	9409	9139.36
"	13	11.4	169	129.96
"	49	47.6	2401	2265.76
"	20	18.2	400	331.24
"	47	45.4	2209	2061.16
"	21	19.8	441	392.04
"	50	49	2500	2401.00
"	28	27	784	729.00
"	34	32.2	1156	1036.84
"	23	21.8	529	475.24
2d	85	83.6	7225	6988.96
"	9	7	81	49.00
"	55	54	3025	2916.00
"	24	22.6	576	510.76
"	61	60.2	3721	3624.04
"	37	35.4	1369	1253.16
"	77	75.6	5929	5715.36
"	35	33.6	1225	1128.96
"	57	55.4	3249	3069.16
"	31	29.8	961	888.04
3d	65	63	4225	3969.00
"	38	36.2	1444	1310.44
"	71	69.6	5041	4844.16
"	26	24.6	676	605.16
"	100	98.4	10000	9682.56
"	54	52.4	2916	2745.76
"	116	114.2	13456	13041.64
"	41	39	1681	1521.00
"	95	92.2	9025	8500.84
"	23	21.6	529	466.56
"	61	58.6	3721	3433.96
"	21	19.6	441	384.16
"	78	76.6	6084	5867.56
"	50	48.6	2500	2361.96
4d	59	57.6	3481	3317.76
"	34	33	1156	1089.00
"	45	43.2	2025	1866.24
"	14	12.4	196	153.76
"	68	66.6	4624	4435.56
"	29	27.6	841	761.76
"	66	64.6	4356	4173.16
"	40	39.2	1600	1536.64
"	94	92.4	8836	8537.76
"	47	45.2	2209	2043.04
"	49	48	2401	2304.00
"	22	21.4	484	457.96

APPENDIX I (cont)

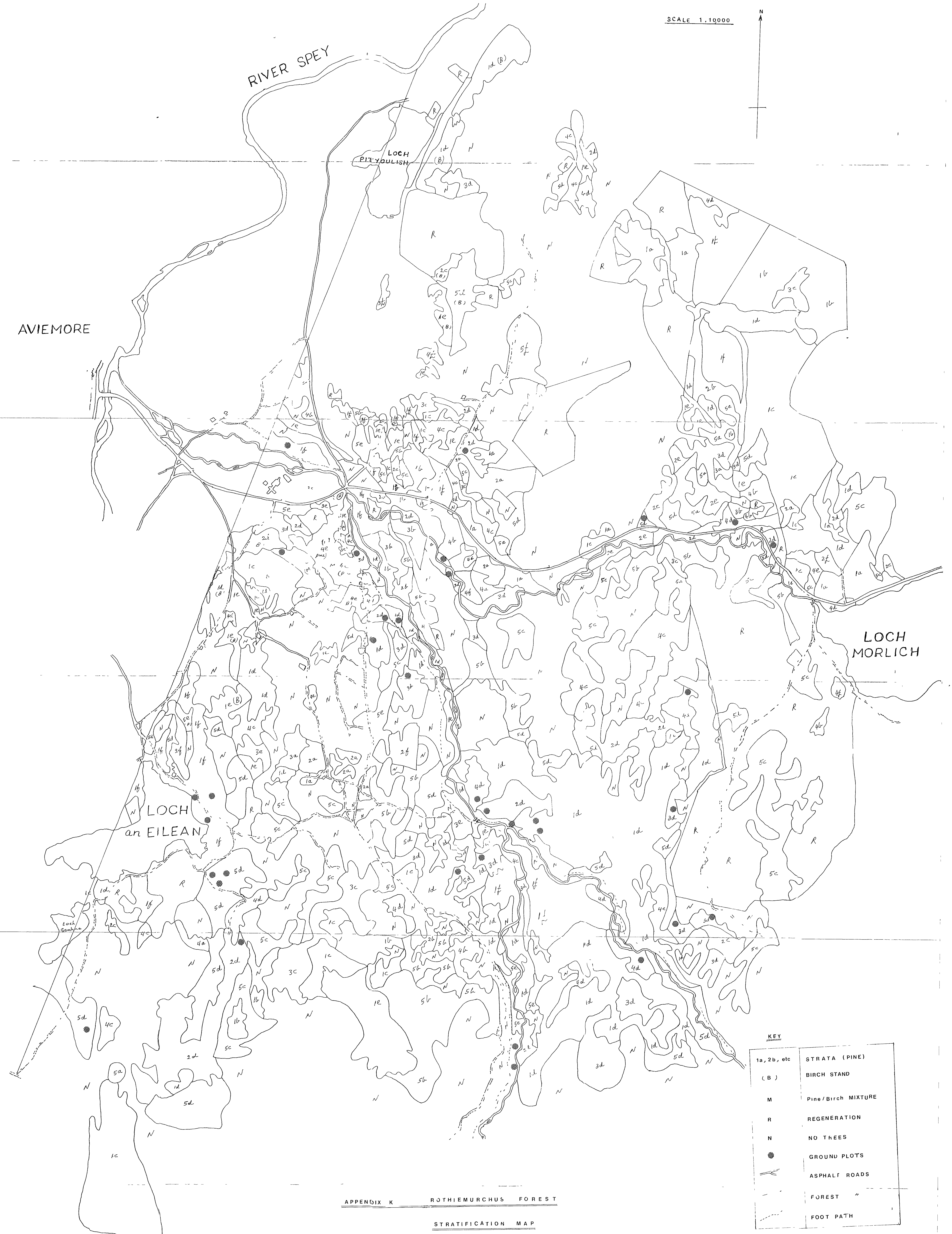
Stratam	DBH_1 (1982)(cm)	DBH_0 (1977)(cm)	$(DBH_1)^2$ (1982)cm^2	$(DBH_0)^2$ (1971)cm^2
5d	68	66.2	4624	4382.44
"	30	28.4	900	806.56
"	75	73.6	5625	5416.96
"	37	35.4	1369	1253.16
"	60	58.8	3600	3457.44
"	19	18.2	361	331.24
"	62	60.4	3844	3648.16
"	34	32.4	1156	1049.76
"	108	106.2	11664	11278.44
"	43	41.4	1849	1713.96
"	104	102.2	10816	10444.84
"	44	41.6	1936	1730.56
"	107	105.2	11449	11067.04
"	17	14	289	196.00
1f	43	42	1849	1764.00
"	27	26.1	729	681.21
"	49	47.8	2401	2284.84
"	30	29.1	900	846.81
"	45	44	2025	1936.00
"	17	16.2	289	262.44
"	52	51.2	2704	2621.44
"	27	26.2	729	686.44
"	18	17.0	324	289.00

Appendix J Calculation of basal area increment per cent.

Stratum	Tree mean size (cm) $\frac{(DBH_1 + DBH_0)}{2}$ (A)	Diameter² ~~Basal Area~~ increment over 5 years ($DBH_1^2 - DBH_0^2$) (B)	diameter² Mean ~~basal area cm²~~ $\frac{(DBH_1)^2 + (DBH_0)^2}{2}$ (C)	Basal Area increment per cent B/C x 100/5
1d	96.3	269.64	9274.18	0.58
"	12.2	39.04	149.48	5.22
"	48.3	135.24	2333.38	1.16
"	19.1	68.76	365.62	3.76
"	46.2	147.84	2135.68	1.38
"	20.4	48.96	416.52	2.35
"	49.5	99.00	2450.50	0.81
"	27.5	55.00	756.50	1.45
"	33.1	119.16	1096.42	2.17
"	22.4	53.76	502.12	2.14
2d	84.3	236.04	7106.98	0.66
"	8.0	32.00	65.00	9.85
"	54.5	109.00	2970.50	0.73
"	23.3	65.24	543.38	2.40
"	60.6	96.96	3672.52	0.53
"	36.2	115.84	1311.08	1.77
"	76.3	213.64	5822.18	0.73
"	34.3	96.04	1176.98	1.63
"	56.2	179.84	3159.08	1.14
"	30.4	72.96	924.52	1.58
3d	64.0	256.00	4097.00	1.25
"	37.1	133.56	1377.22	1.94
"	70.3	196.84	4942.58	0.80
"	25.3	70.84	640 .58	2.21
"	99.2	317.44	9841.28	0.65
"	53.2	170.24	2830.88	1.20
"	115.1	414.36	13248.82	0.63
"	40.0	160.00	1601.00	2.00
"	93.6	524.00	8762.92	1.20
"	22.3	62.44	497.78	2.51
"	59.8	287.04	3577.48	1.60
"	20.3	56.84	412.58	2.76
"	77.3	216.44	5975.78	0.72
"	49.3	138.04	2430.98	1.14
4d	58.3	163.24	3399.38	0.96
"	33.5	67.00	1122.50	1.19
"	44.1	158.76	1945.62	1.63
"	13.2	42.24	174.88	4.83
"	67.3	188.44	4529.78	0.83
"	28.3	79.24	801.38	1.98
"	65.3	182.84	4264.58	0.86
"	39.6	63.36	1568.32	0.81
"	93.2	298.24	8686.88	0.69
"	46.1	165.96	2126.02	1.56
"	48.5	97.00	2352.50	0.82
"	21.7	26.04	470.98	1.11

APPENDIX J (cont)

Stratum	Tree mean size (A)	Diameter² ~~Basal area~~ increment over 5 years (B)	Mean diameter² ~~basal area~~ (C)	Basal Area increment per cent B/C x 100/5
5d	67.1	241.56	4503.22	1.07
"	29.2	93.44	853.28	2.19
"	74.3	208.04	5520.98	0.75
"	36.2	115.84	1311.08	1.77
"	59.4	142.56	3528.72	0.81
"	18.6	29.76	346.12	1.72
"	61.2	195.84	3746.08	1.05
"	33.2	106.24	1102.88	1.93
"	107.1	385.56	11471.22	0.67
"	42.2	135.04	1781.48	1.52
"	103.1	371.16	10630.42	0.70
"	42.8	205.44	1833.28	2.24
"	106.1	381.96	11258.02	0.68
"	15.5	93.00	242.50	7.67
1f	42.5	85.00	1806.50	0.94
"	26.6	47.79	705.11	1.36
"	48.4	116.16	2342.92	0.99
"	29.6	53.19	873.41	1.22
"	44.5	89.00	1980.50	0.90
"	16.6	26.56	275.72	1.93
"	51.6	82.56	2662.72	0.62
"	26.8	42.56	707.72	1.20
"	54.6	87.36	2981.32	0.59
"	17.5	35.00	306.50	2.28



APPENDIX K ROTHIEMURCHUS FOREST

STRATIFICATION MAP